DEVIATION
AND THE
DEVIASCOPE

Including the Practice and Theory
of
COMPASS ADJUSTMENT

By

CHARLES H. BROWN,
F.R.S.G.S.

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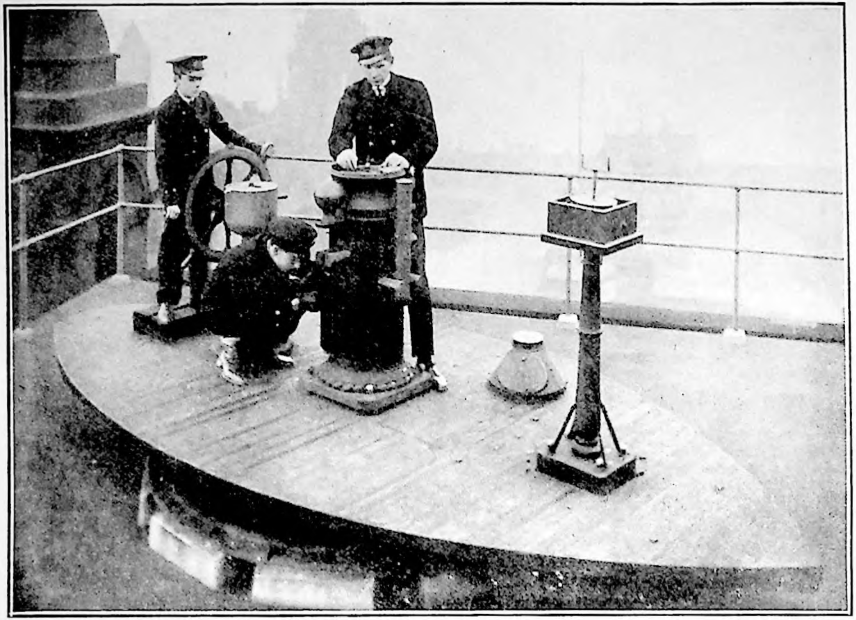
C. H. BROWN



Frontispiece.]

ROOF DEVIASCOPE

DEVIATION AND THE DEVIASCOPE

INCLUDING THE PRACTICE AND THEORY OF

COMPASS ADJUSTMENT

ALSO

A NOTE ON THE GYRO-COMPASS

BY

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REVISED AND ENLARGED

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PREFACE.

THE substitution of iron for wood, in the construction of ships, introduced a serious problem in navigation by surrounding the mariner's compass with a multitude of magnets.

Navigators of wooden ships noticed that the compass did not usually point "true as the needle to the pole," but the first systematic investigations into the subject of ship magnetism were made by Captain Flinders, R.N., the "Flinders Bar" being a lasting testimony to the practical value of his researches. It was due, however, to the experiments of Sir George B. Airy, K.C.B., F.R.S., Astronomer Royal, and on his recommendations that the method, still employed, of tentatively adjusting the compass by magnets and soft iron was introduced.

The Liverpool Compass Committee during 1855 and subsequent years made searching inquiry into the magnetic condition of a number of merchant ships and the deviation of their compasses, under a variety of conditions in different parts of the world, and the labours of this Committee, which were gratuitously given, added much information of a practical character to a comparatively new subject.

The mathematical aspect of the subject was afterwards reinvestigated and published in the *Admiralty Manual, Deviations of the Compass*. The Admiralty, meantime, established a Compass Department under the Hydrographic Office, and the compass with its adjuncts have, for many years, been the subject of special examination and study, indeed the publications of His Majesty's Government form the principal source of our information on the deviation of the compass.

But it was not until 1876, when Sir William Thomson (Lord Kelvin), Professor of Natural Philosophy in the University of Glasgow, produced the epoch-making Thomson Compass that navigators were provided with a really reliable instrument. Since then the progress made in this branch of physical science has been chiefly in the direction of instrumental improvements.

The liquid compass has now superseded the dry card in ships of the Royal Navy where the vibration of powerful engines, and jolting due to the concussion of gunfire, is sometimes excessive, and in certain types

of warships in which the surrounding masses of iron have almost cut off the compass from the directive influence of the earth's magnetic force, the motor driven gyroscopic compass has been introduced, but in merchant ships the magnetic compass is universally adopted.

Perhaps no navigational subject lends itself more readily to experimental work in a laboratory than that of compass adjustment. The effect of ship magnetism on the compass can be demonstrated in all its phases, and the subject revealed to the student in a more satisfactory manner than is possible on board ship, and where apparatus, such as shown in the frontispiece, is available for outside work, the several methods of ascertaining the deviation and the process of compensation may be performed ashore in precisely the same way as practised by adjusters when swinging ship.

This book is arranged on the lines followed usually in Navigation Schools when presenting the subject to students attending short courses of instruction. The work is mainly descriptive, and students are recommended to frame an answer to the questions given in the book immediately on reading the chapter to which they relate.

I am indebted to the Lords Commissioners of the Admiralty for permission to reproduce Tables and Charts from the *Admiralty Manual, Deviations of the Compass*; to Messrs. J. D. Potter, London, and Messrs. Brown, Son & Ferguson, Ltd., Glasgow, for extracts from their publications; to Messrs. Henry Hughes & Son London; Messrs. Kelvin, Bottomley & Baird, Glasgow; The Sperry Gyroscope Coy., Ltd., London, and Messrs. Baird & Tatlock, Glasgow, for permission to reproduce illustrations of instruments manufactured by them.

C. H. B.

GLASGOW, 1936.

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BY APPOINTMENT TO THE UNIVERSITY

CONTRACTORS TO H.M. GOVERNMENT

No 5911

KELVIN, BOTTOMLEY & BAIRD, LTD.

Magnetic Observatory,
Jordanhill.
GLASGOW. Dec 8 1913

This is to Certify that Compass Card No. 22288 belonging to Bowl No. 11050 has been tested in our Magnetic Observatory at Jordanhill, Glasgow, and has been adjusted within the following limits of accuracy when freely suspended in the earth's undistorted magnetic field.

The Radial line from centre point to North cardinal point of card lies within 5' E of Magnetic North

The Radial line from centre point to East cardinal point of card lies within 6' S of Magnetic East

The Radial line from centre point to South cardinal point of card lies within 4' W of Magnetic South

The Radial line from centre point to West cardinal point of card lies within 2' N of Magnetic West

The period of oscillation of the card under the above named conditions (at Glasgow) is 33 seconds.

The weight of the card is 225 grains

Deflection of auxiliary magnet at a distance of 229 millimetres is 14 deg

The lubber point, azimuth graduated circle and suspension system have been tested with relation to one another and accurately adjusted.

JR.

Signature J. T. Bottomley

Chairman of KELVIN, BOTTOMLEY, & BAIRD, LTD

TRADE MARK

Deviation and the Deviascope.

CHAPTER I.

1. **The Reliability of the Mariner's Compass** as an unerring guide for the navigator is impaired somewhat by several defections of a more or less elusive character.

There is always, for example, the possibility of imperfect workmanship, but this source of error is almost entirely eliminated in well designed compasses. Then there are limitations imposed by terrestrial magnetism on the directional properties of the magnetic needle, the power with which it points northward varying to such an extent that, in very high latitudes, it is rendered almost useless for the purposes of navigation. Lastly, there are those ever varying, inconstant deflections of the compass needle to the right or left of the magnetic meridian, comprehensively styled deviation, and which are due to the magnetic condition of the ship, her equipment and cargo.

We propose to discuss these several features in the following order, namely—the mechanism of the compass, terrestrial magnetism including the general properties of a magnet, and lastly, the deviation of the compass.

2. **The Ideal Compass Card** should be as light as gossamer, have great directive power, and a long period of vibration. A certain amount of material must, of course, enter into its construction, but if it be too heavy frictional error is caused which is highly objectionable. Lord Kelvin, by a judicious combination of the lightest of materials, such as rice paper, silk threads, and aluminium, reduced the weight of the old 10-inch dry card from 1600 grains to 190 grains.

It is extremely difficult to combine great directive power with a long period of vibration, as these characteristics are antagonistic. If the needles be strong the period of the card is shortened, and the compass will probably be unsteady at sea. If, on the other hand, the needles be too weak, the period will be too long, the compass will be

slow in coming to rest, and consequently fail as an instrument of direction.

The efforts of the compass maker is therefore directed towards obtaining a satisfactory combination of these opposing elements, in order to produce a card of minimum weight and maximum directive power, consistent with a period of oscillation suitable for the purposes of navigation.

3. Short Needles are best.—The directive force of a needle is limited by the earth's magnetic influence and the capacity of the needle to absorb and retain magnetism.

Two or more needles, an equal number placed in definite positions, on each side of the centre of the card and all exactly parallel to each other, are more effective than a long single needle. In the Thomson standard pattern 10-inch dry card, universally adopted in merchant ships, eight needles are used, four on each side of the centre of the card, the longest of which measures 3.5 inches (*see* fig. 1).

FIG. 1.

4. A Mechanical Couple.—When two parallel forces act at different points on a lever a turning force, called a couple, is introduced which can only be neutralised by another couple tending to produce rotation in the opposite direction.

The compass needle is the lever in this case. It is turned by the magnetic forces in the ship, a counter turning movement being produced by magnets and iron correctors. The moment, or turning power of a magnet, is equal to the product of its pole strength and the distance between its poles.

A system of short needles is less likely to magnetise nearby correctors by induction than a long, single needle, thus creating a more uniform magnetic field.

5. A Few Important Details.—It is essential in the perfect compass that the card should be extremely light in order to reduce frictional resistance at the point of suspension.

The jewelled cap should be of sapphire, highly polished and free from cracks; the pivot should be a sharpened point made of iridium. The card must be accurately centred and graduated. The magnetic axis of the needles, that is the line joining the poles of the needles, should be exactly parallel to a line drawn through the north and south points of the card. When the card is deflected and allowed to swing, it should always come to rest indicating the same direction.

Skilful Workmanship.—The Admiralty reject compass cards having an index error arising from mechanical defects of more than 10 minutes of arc. (A copy of the certificate issued with the compass mounted on the roof deviascope, shown in Plate I., is given on page xii.)

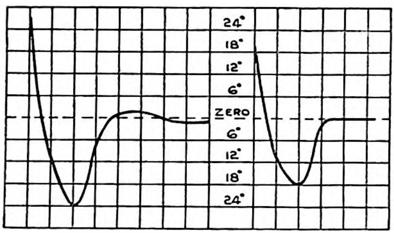
6. The Period of the Card.—If a compass card is deflected to one side, then released, and allowed to swing to and fro until it comes to rest, the average time occupied in swinging through its extreme deflection from, say, right to left and back again to the right, is called the period of the card.

It is undesirable that the period of the card should be the same as the period of the ship's roll. If the swing of the card and the roll of the ship synchronised, the result would be a most objectionable compass in bad weather, as the card would be kept continuously on the swing by the momentum imparted to it from the rolling of the ship. The period of the Thomson 10-inch card, with eight needles, is about 33 seconds, which is far slower than the roll of an average ship. Greater steadiness is obtained when the bulk of the weight is thrown on to the outer rim of the card, and this object is attained by fixing to its edge an aluminium ring, which also imparts strength and rigidity. The centre of gravity is kept below the point of suspension as this enables the card to keep horizontal in all latitudes. The vibration of the hull due to pitching, rolling and high powered engines sometimes produces an unsteadiness of the compass and efforts have been made to reduce this oscillating movement.

A dry card when deflected 90° oscillates for some time before it comes to rest, the retarding or damping effect of the air being about 20 per cent. The liquid compass is designed to provide a steadier card, its movements are more sluggish owing to the friction of the liquid, the damping effect of which is about 60 per cent., but although it is steadier and comes to rest from a disturbance of 90° after making usually 1½ complete periods of oscillations it is not so easily adjusted owing to the long needles.

An "aperiodic" card has no period, that is one which when deflected comes to rest dead-beat. without swinging past the lubber line.

The nearest approach to this type is the Campbell-Bennett Patent Compass known to-day as the "Dead-beat" compass. It comes to rest in 40 seconds from a disturbance of 90° without making one complete period of oscillation. The damping effect is about 80 per cent. due to the introduction of eight radial filaments of wires underneath the card, which makes it non-oscillatory by their high eddy resistance as they move through the liquid. The needle is 2½ inches long and, in common with all short needle compasses, this is a great advantage when adjusting. The diagram illustrates the oscillation of the two types of liquid compasses from a deflection of about 20° until they come to rest.



The Chetwynd Liquid Compass. The Dead-beat Compass.

7. The Bowl and the Binnacle.—The bowl is made of copper or brass, slung in gimbals and weighted at the bottom to assist it to keep upright. The compass needles and the centre of the quadrantal corrector should all

be in the same horizontal plane. The lubber line must represent accurately the fore and aft line of the ship. Provision should be made in the binnacle to receive the fore and att and athwartship magnets used for adjusting the compass, also for the bucket which holds the vertical magnets required to correct the heeling error.

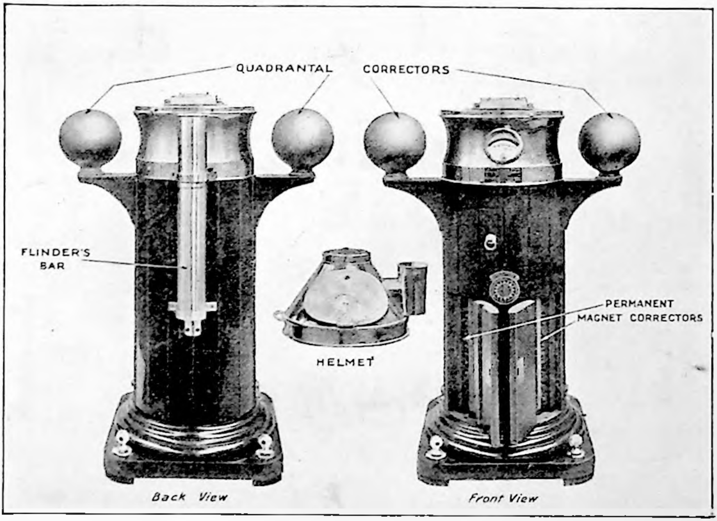


FIG. 2.—STANDARD COMPASS.

8. Position of Standard Compass.—The most troublesome source of compass error is that due to the magnetic influence of the ship. Great care should therefore be exercised when selecting a position for the compass so that the deviation on the uncorrected compass will be as small as possible, thereby reducing the extent of the trouble. The less deviation there is to correct the better. If, for example, the compass is placed in the middle line of the ship, the effect of vertical iron on one side will be automatically counteracted by similar upright iron on the other side.

In merchant ships the standard compass is placed high above the hull in a position from whence a clear all-round view of the horizon

can be obtained, and convenient for taking bearings. The compass must be placed at least 5 feet away from iron of any kind, especially moveable iron, such as ventilators and davits. The ends of iron beams and uprights must be particularly guarded against.

Dynamos have been known to affect the compass at a distance of 50 feet and leakage of electric current from wireless plant may also deflect the needle. All electric cables near the compass should be twin wire, so that the effect of positive and negative currents may neutralise each other. The compass should be tested with electric lights on and off

FIG. 3.—A LIQUID COMPASS.

9. **The Liquid Compass.**—In warships where concussion or jolting due to gunfire is very great, or wherever vibration is excessive, steadiness of the card is ensured by immersing it in liquid composed of two parts of distilled water and one of alcohol. Liquid compasses form part of the statutory equipment of ships' lifeboats.

The needles are encased in brass to prevent rust. The card is mounted in the same way as the dry card, care being taken to keep its centre of gravity below the centres of flotation and suspension. The sapphire cap of the card rests lightly on the iridium point, the weight on the pivot being about 100 grains.

The air is extracted from the bowl before the cover is finally screwed down, and the bowl must be kept absolutely filled with th

liquid and kept free of air bubbles. An elastic metal chamber responds to the expansion and contraction of the liquid due to changes of temperature.

Disturbing eddies may be set up in the liquid between the edge of the card and the bowl when the ship's head is swung rapidly. This is obviated, however, by reducing the diameter of the card, as in fig. 4.

FIG. 4.—REDUCED DIAMETER CARD LIQUID COMPASS.

Stowage of Magnets.—Compass cards should be handled with great care. They are very delicate, and indispensable to the mariner. When stowing away spare cards the north point of one should be placed next to the south point of the adjacent card. Better stow them on top of each other, the north of one card being placed over the south of the other. The same rule applies to magnets. Keep

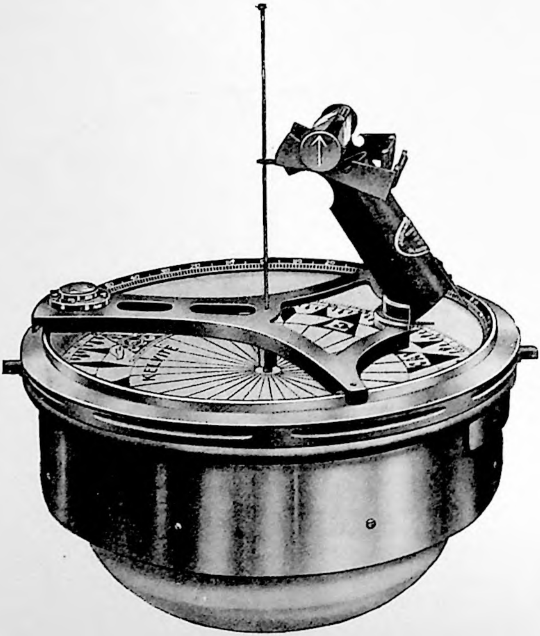


Fig. 5.—Kelvin Azimuth Mirror.

unlike poles together, so that their magnetic power may be preserved if not intensified. No compass cards or magnets to be placed near chronometers, otherwise the steel parts may be magnetised.

10. Azimuth Mirror.—The bearing of an object may be taken by means of the Kelvin azimuth mirror (fig. 5) with the "arrow down" or the "arrow up." The former is used for a low-lying object, its direct bearing being got by keeping the eye in the horizontal plane of the mirror, and looking at the object over the top of the prism, and turning the prism until the reflection of the degrees of the compass card are seen at the same time as the object.

For elevated objects, especially celestial bodies, the method of "arrow up" is used. Look down the tube, and turn the prism until the refracted image of the body is seen at the edge of the compass card, then read off the bearing. Care should be taken to ensure that the pointer of the mirror is directed towards the refracted image of the object, especially when the altitude of the body exceeds 40°, otherwise an appreciable error may be introduced.

The adjustment of the prism may be tested by noting the bearing of a fixed object with the "arrow up" and "arrow down." The refracted bearing and the direct bearing should agree. If not, the prism may be adjusted by means of its securing screws.

11. The Pelorus is an auxiliary instrument used in compass adjustment to steady the ship's head in any required direction when the magnetic bearing of a distant object is known. It is also used at sea to get the bearing of an object which may be shut out from view at the compass by the funnel or deck erections.

There are various patterns. (*See* fig. 6.) The essential parts are a circular bearing plate, graduated in the same way as a compass card, mounted on a vertical axis so that it rotates freely. It is fitted with a lubber-line and sight vanes, also with clamp screws arranged so that the plate and the sight vanes may be clamped either together or independently of each other.

Suppose it is desired to get the bearing of an object situated well out on the quarter or nearly right astern. Place the pelorus in the position prepared for it, usually in the wings of the bridge. The lubber point must indicate correctly the fore and aft line of the ship. The quartermaster calls out the direction of the ship's head by the compass to the operator at the pelorus, who turns the bearing plate round until the lubber point is at the same direction. The pelorus

now indicates exactly the same direction as the compass, then by directing the sight vanes to the object its bearing can be read off the dumb card.

If it is desired to steady the ship's head on, say, N. 30° E magnetic by means of a shore object whose bearing is, say, N. 40° W. magnetic, we would proceed as follows :—Turn the bearing plate round until the required course (N. 30° E.) is at the lubber point, then clamp the sight vanes to the known magnetic bearing of the object (N. 40° W.). Swing ship, and, when the object comes into the sight vanes her head will be in the required direction, N. 30° E. magnetic. Or, we may

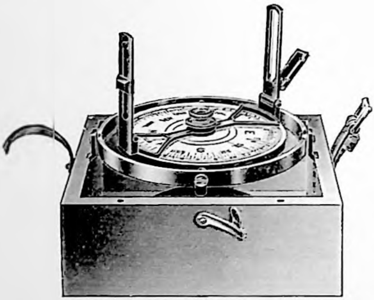


FIG. 6—ADMIRAL FRIEND'S PELORUS, BY MESSRS. HEATH & CO., LTD.

wish to know the deviation for the course the ship is steering. Suppose she is heading S. 30° E. by compass, and the magnetic bearing of the shore object is S. 10° W.; required the deviation. Clamp the sight vanes and the bearing plate together at the magnetic bearing (S. 10° W.). The vanes and the bearing plate being clamped to each other they rotate together, so turn the plate round until the vanes are directed to the object, the lubber line of the pelorus will then indicate the magnetic direction of the ship's head, say, S. 35° E. and the difference between this direction and the ship's head by compass will be the deviation.

S. 35° E. (mag.) – S. 30° E. (comp.) = 5° W. Dev.

Lifeboat Compasses. The compass must be of liquid type, the mixture being two parts of unpotable methylated spirits and three parts of distilled water.

The card must have ample directive force and a period of 18 to 22 seconds after a deflection of 40° at a temperature of about 60° Fahr. It must be graduated to $\frac{1}{4}$ points, be not less than 4 inches in diameter, have a clearance from the bowl of at least $\frac{1}{4}$ inch and its weight, when submerged, should be between 4 and 6 grammes on the pivot.

The cap must be a hard jewel, the pivot of iridium and the bowl must be weighted at the bottom, fitted with gimbals giving fore and aft and athwartship action, placed in a box and lit by an oil lamp to burn for 10 hours. The maker's name and address must be shown on the card or float.

Compasses should be periodically tested, overhauled and repaired as they receive distinctly hard usage.

North Atlantic passenger ships fitted with wireless telegraphy need only provide four rowing boats and every motor boat with compasses, but these boats must be marked distinctively.

QUESTIONS.

1. State briefly (*a*) the essentials of an efficient compass; and (*b*) what you would consider a good arrangement of the needles (that is whether long or short, single or double, etc.) with a view to good compensation. *See* paragraph, (3) (5) (7).

2. State briefly the chief points to be considered when selecting a position for your compass on board ship, and what should be particularly guarded against? (8)

3. In stowing away spare compass cards or magnets how would you place them with regard to each other, or what might be the probable consequence? (9) (20)

4. What is meant by the period of the card? (6)

5. Describe the special features of the liquid compass. (9)

6. Describe a "dumb card" or "pelorus" and the method of using it to get the bearing of an object. (11)

7. When a compass is lighted by electricity why should single wiring be avoided? (pages 6 and 136).

8. Describe the various compasses used in merchant ships. Which do you prefer and why?

9. What do you consider an efficient boat compass? (9)

CHAPTER II.

12. **What is Magnetism ?**—Magnetism is a mysterious force of Nature made manifest on the earth and in the atmosphere surrounding the earth. Although the source of this persistent and penetrating power is hidden from us, yet slowly, by the collection of facts, revealed by long and continuous investigations, definite laws have been established, which express with considerable accuracy the physical relationship existing between the earth and a magnetised needle, as well as the reciprocal action which takes place between artificial magnets.

13. **The Earth an Irregular Magnet.**—The apparent effect of terrestrial magnetism on the compass needle appears to be due to currents of electricity passing round the earth, as if the earth were an electro-magnet. Much of the phenomena, however, can also be explained by conceiving the earth to be an irregular magnet, and considered as such, it will help towards a clearer understanding of our subject if we first review a few of the general properties of a magnet.

14. **The Lodestone.**—The dark grey coloured lodestone widely scattered throughout the earth is found to possess some peculiar properties. Dip a piece of this stone into iron filings and on withdrawal tufts of filings will be found adhering to it. Mount an elongated piece of lodestone on a vertical axis, so that it may turn freely, and it will point lengthwise in a northerly direction. If deflected, it will vibrate to and fro for a time, but will persistently come to rest in the same definite direction. Hence the name lodestone, from the Anglo-Saxon word " loedan," meaning to lead.

15. **An Artificial Magnet.**—By drawing a piece of lodestone over a needle a few times in the same direction—not backwards and forwards—the natural properties of the lodestone become manifest in the needle. The needle is now an artificial magnet. Suspend the

magnet so that it can turn freely and it will take up a north and south direction.

16. **The Three R's and Three U's.**—The north seeking end of a magnet is termed the north, or red, or marked end, to distinguish it from the south, or blue, or unmarked end.

noRth,	Red,	maRked.
soUth,	blUe,	Unmarked.

17. **The Poles of a Magnet.**—Near each end of a magnet are two points of maximum magnetic power. These points are its poles, and the distance between them is called the axis of the magnet. The poles are equal in power but opposite in name, that is to say, the attractive power of one pole is equal to the repulsive power of the other. The effect of the magnet diminishes towards the middle, and midway between the poles its effect is neutral.

18. **Magnets *ad libitum*.**—Break the magnet in two, and two complete magnets are formed, each with its red and blue pole. Break up the magnet into many pieces, and every individual piece will be a perfect magnet ; the red pole cannot exist without the blue ; they are wedded to each other.

19. **How to make a Magnet.**—Magnets of small power can be easily made by the method of divided touch.

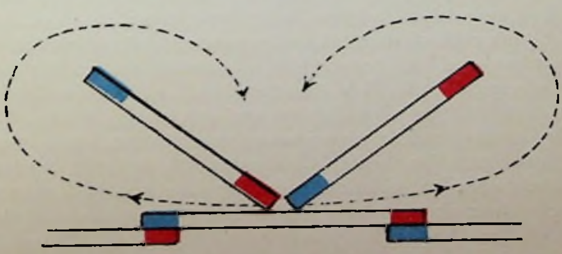


FIG. 7.—MAKING A MAGNET.

Support the ends of the bar to be magnetised on the opposite poles of two other magnets placed end on to each other at a convenient

distance apart as in fig. 7. Then place the opposite poles of two magnets at the middle of the bar, and draw them simultaneously, a few times, from the middle to the ends. Turn the bar over, and stroke the other side in a similar manner. Observe that the north pole induces blue polarity, and the south pole red polarity in the bar.

20. **Saturation.**—It will be found that the capacity of the bar to absorb magnetism is soon reached ; it is then saturated. The magnetism in the bar may be diminished by bringing it in contact with another magnet, similar poles together, and completely demagnetised by heating it to a high temperature.

Compound magnets such as those used for compass needles and for compensation are produced by drawing a steel bar from end to end over one pole of an electro magnet, then drawing it in the opposite direction over the other pole.

When a magnet is heated slightly it becomes less magnetic, but on cooling it recovers its magnetic strength. If heated to 100° C., for example, the magnet is not only less magnetic when hot, but fails to regain its former power when cooled ; if heated to 200° it loses permanently more of its magnetism when cooled, and proportionately more when heated to 300° and cooled again ; and so, with every increase in temperature a magnet loses permanently more and more of its losable magnetism until, eventually, when heated to a critical temperature of 700° to 800° centigrade it loses all its magnetism and is completely demagnetised when cooled.

The quality of the steel determines its magnetic permeability, the best permanent magnets being made from steel containing about 5 per cent. of tungsten and ·6 per cent. of carbon. Steel is "glass hardened" by heating it to a bright red and cooling it in a bath of vegetable oil ; it is then very hard and brittle and readily broken. If, instead of cooling the steel by plunging it into oil, the red hot steel is covered with red hot ashes and left until the ashes are cool it becomes flexible and is known as soft steel. In neither of those extremes is steel suitable for magnetisation, the best results being got from glass hardened steel heated to a temperature of about 300° centigrade when it appears as a deep blue tint, and then tempered.

21. **The Magnetic Field.**—Magnets emit from their poles a continuous stream of magnetism which follows well defined curves known as lines of force. The space covered by these lines of force

and through which the influence of the magnet extends is called its magnetic field.

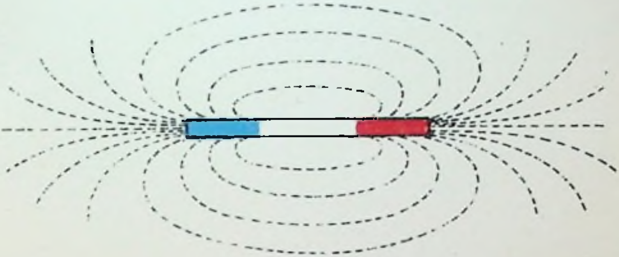


Fig. 8.—Lines of Force.

These stream lines on emerging from the magnet are crowded together, but they immediately afterwards begin to spread out, some forming a closed curve by returning to the magnet, while others

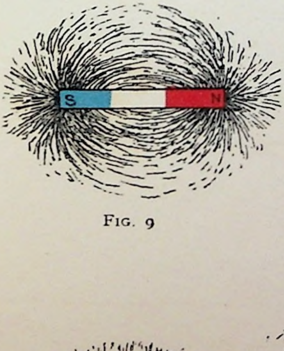


Fig. 9

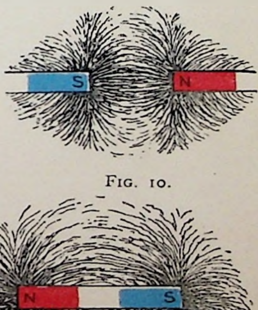


Fig. 10.

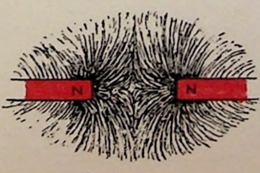


Fig. 11.

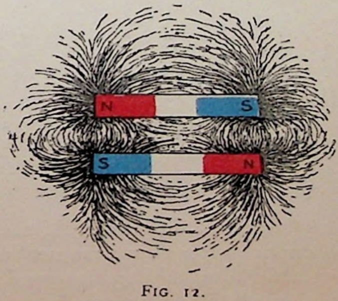


Fig. 12.

are lost in space. When the lines of force are greatly congested the inductive force of the magnet is increased, hence the reason why a bar of iron is strongly magnetised when held close to a magnet, as it then receives a greater number of the lines of force.

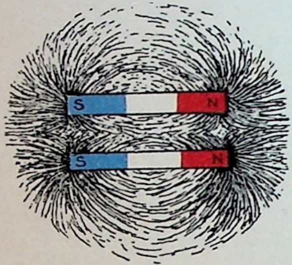
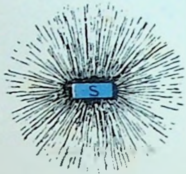


FIG. 13.



LINES OF FORCE OVER A SINGLE POLE.

FIG. 14.

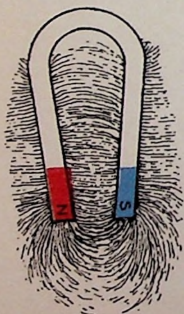


FIG. 15.

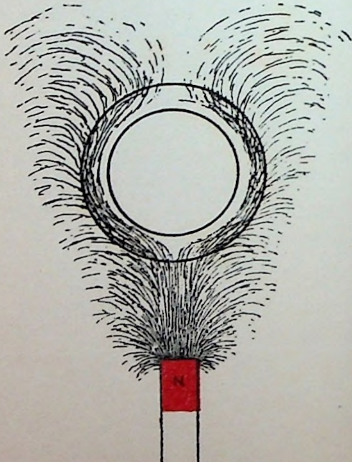


FIG. 16.

The lines of force from a magnet may be mapped out by placing a sheet of paper over a magnet and sprinkling iron filings on its surface. When the paper is tapped the filings arrange themselves in the very definite directions shown in figs. 9 to 16.

It will be noted that the several combinations of magnets do not destroy the lines of force but merely bend them into a new shape; the modification of their path depends on the obliquity of the angle at which the flow lines meet, the resultant direction thus representing the path along which a free speck of red magnetism would appear to travel. The lines in the figures are mapped in the plane of the paper, but it is to be understood that they enclose the magnet all round in a flux, a magnetic atmosphere, or field, the lines of energy radiating from the poles in much the same way as sprays of water from the nozzle of a vertical fountain. Fig. 16 represents a cross section of a spherical shell. The lines of force from the magnet bend to the shape of the sphere leaving the central space non-magnetic. A needle placed inside the sphere would be cut off from the influence of all outside magnets, it would be perfectly screened. This is practically what happens at a compass inside a submarine, the needle is cut off by the hull from the earth's magnetism.

22. Law of Inverse Squares.—The magnetic force exerted at any point in the field varies inversely as the square of its distance from the magnet, but the deviation produced varies inversely as the cube of the distance, and may be roughly demonstrated at the deviascope. Steady the ship's head on north and, as the north point is then at the lubber line, this will ensure that the needle is lying in the fore and aft line of the model. Place a magnet at A, fig. 17, in

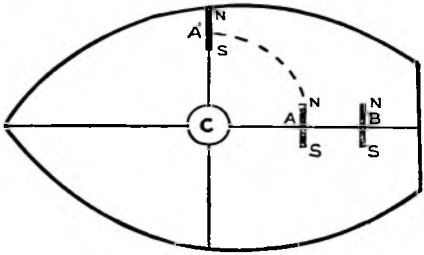


FIG. 17.

the same horizontal plane as the needle and, for the purposes of illustration, 8 inches from the centre of the compass. Note the deflection of the north from the lubber line: assume this deviation to

be 10°. Now move the magnet back to B, say 12 inches from the centre of the compass, the deviation produced will probably be 3°. This experiment may be stated in the form of a question and checked by calculation.

EXAMPLE:—A magnet produces 10° deviation when 8 inches from the centre of the compass, find the deviation it will produce when it is 12 inches from the centre of the compass, the magnet in both cases being broadside on.

$$\frac{\text{The required dev.}}{\text{The known dev.}} = \frac{(\text{the distance of magnet for known dev.})^3}{(\text{the distance of magnet for required dev.})^3} = \frac{CA^3}{CB^3}$$

$$\frac{X^\circ}{10^\circ} = \frac{8^3}{12^3} \quad \therefore \quad X^\circ = \frac{10 \times 8 \times 8 \times 8}{12 \times 12 \times 12} = 3^\circ$$

Various distances of the magnet from the compass may be tried experimentally and the results checked by calculation. If the magnet A be moved round parallel to itself to position A^1 its centre being still 8 inches from the centre of the compass, it will deflect the needle 20° because the capacity of a magnet to do work when "end on" (position A^1) is double its energy when "broadside on" (position A). The best results are obtained when the compass needle is very short in comparison to the length of the magnet. See also p. 161.

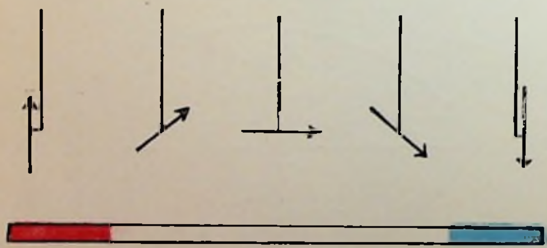


FIG. 18.

23. Unlike Poles attract; like Poles repel.—Place a magnet on a table and pass a freely suspended needle over it from end to end. The north or red end of the needle is attracted by the blue pole of the

magnet, and the south end of the needle is equally attracted by the red pole of the magnet. When held midway between the poles the needle lies horizontal, but on approaching the ends of the magnet the needle points more and more downwards until eventually it stands vertical when held over the poles. At any position in the field of the magnet, a freely suspended needle will always come to rest when pointing towards the pole of the magnet.

24. **Analogy between a Magnet and the Earth.**—Practically the same features appear on the earth's surface when a freely suspended needle is passed from pole to pole. The phenomena are similar to

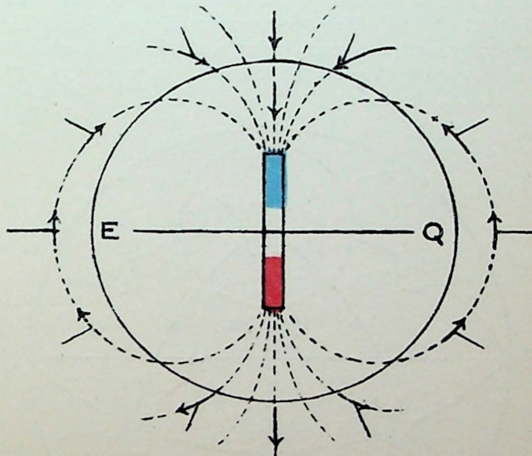


FIG. 19.—THE EARTH A MAGNET.

what would be expected if a huge magnet were situated inside the earth, nearly coincident with its axis of rotation, and flooding the north hemisphere with blue polarity and the south hemisphere with red. Near the geographical equator the needle takes up a position parallel to the earth's surface. On approaching the poles, the north or red end of the needle dips downwards in the north hemisphere, but points upwards in the south hemisphere, making an ever-increasing angle with the plane of the horizon until eventually the

needle stands upright over an area covering some 50 miles or more of the earth's surface. This region is called the magnetic poles, the accepted positions being :—North pole about lat. 70° N., long. 97° W.; south pole about lat. 72° S., long. 154° E.

25. **The Magnetic Equator.**—A curve passing through places where there is no dip or inclination of the needle is called the magnetic equator. It is the dividing line between the red and blue polarities of the earth. The magnetic equator crosses the geographical equator from south to north in about 12° west longitude, and tracing it to the eastward, it reaches as far as 10° north latitude passing near Cape Guardafui. It then converges slowly with the geographical equator, which it re-crosses in about 170° west longitude and attains its maximum south latitude, 14°, in Brazil, when it again bends northward and rejoins the equator in 12° west. *See* Chart I. at the end of the book.

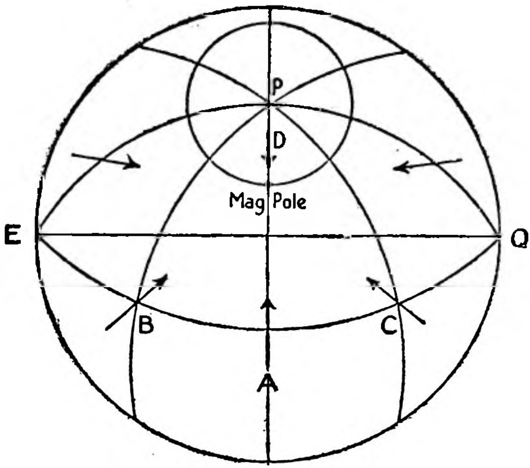


FIG. 20.

26. **Variation of the Compass.**—The direction from any position on the earth's surface to the geographical pole is represented by a true meridian.

The direction taken up by the longitudinal axis of a compass needle when under the influence of the earth's normal force only is called the magnetic meridian.

Variation at any place is the angle contained between the true and magnetic meridians at that place, and is caused by the geographical and magnetic poles not coinciding.

The amount of variation depends on the parallactic angle subtended by the magnetic and geographical poles and varies in navigable latitudes from 90° E. to 90° W., being named East or West according to whether the needle points respectively to the right or left of the true meridian.

In figure 20 the variation at place *A* is 0°, at *B* it is easterly, at *C* westerly, at *D* a position between the two poles the variation is 180°, the needle being turned end for end, so that when making southing the ship's head would appear to be northerly by the compass.

27. Variation Changes.—The variation in addition to being different at different places is subject to a gradual change, the amount in Great Britain being at the rate of 8′ annually. This secular change is probably due to the magnetic poles changing their position relatively to the geographical poles.

28. An Illustration.—The south point of Africa, L'Agulhas, the needle, was so named by the Portuguese who discovered it from the fact of the compass needle in its vicinity pointing to the true north. At present, in the same position, the variation is 28° W.

On the Clyde, 260 years ago, the variation was 0°, to-day it is 18° W.

29. The Variation Chart.—The Admiralty issues a special chart which shows curves drawn through places having the same variation. These irregular curves are named isogonic lines, from the Greek word *isos*, meaning equal, and *gonia*, an angle.

This chart is specially useful in the practice of navigation because the variation may change rapidly when the ship is sailing across the lines, especially so if the course lies at right angles to them, and, as prospective changes in the variation are readily got from the chart, the compass course can be altered correspondingly from time to time.

It will be noted on examining Chart I. that the variation changes rapidly on the trans-Atlantic tracks, particularly in the English Channel and its approaches, also on the East Coast of the United States, the Brazilian Coast, and the West Coast of Australia.

It should also be remembered when working up the true bearing of a celestial body by altitude-azimuth, or time-azimuth tables, that the angle between the true and the compass bearing of the body gives the error of the compass, and by eliminating the variation got from the chart the deviation is found as follows:—

True bearing of body, say, - -	N. 34° E.
Compass ,, ,, - - - -	N. 20 E.
Error of the compass - - - -	14 E.
Variation from chart - - -	18 E.
Deviation for ship's head	4 W.

The variation at a place is the angle contained between the planes of the geographical and magnetic meridians. This angle may be found approximately correct without the aid of special magnetic instruments such as "declinometer," or the "unifilar declination magnetometer," by simply landing a compass ashore and mounting it in a position free from local magnetic attraction, so that it may be under the influence of the earth's normal force only, the axis of the compass needle will then be in the plane of the magnetic meridian, and the bearing of any object read from the compass will be the magnetic bearing of that object. The difference between the magnetic bearing and the true bearing is the variation.

The true bearing of an object on the horizon may be found by measuring with a sextant the angular distance between the centre of the sun and the object, as represented by the arc *X B* in fig. 21 and at the same time observing the sun's altitude, the arc *A X*. With these two arguments the arc of the horizon *A B* may be calculated. The true bearing of the sun (arc *N A*) for the time of observation having been got from azimuth tables, or by alt-azimuth calculation, the difference between the arcs *A B* and *N A* will give the arc *N B* which is the true bearing of the object. Suppose the observer to have been standing at position *C* beside a compass quite free from local magnetic attraction, then the bearing of the object as indicated by the compass (the arc *M B*) would be correct magnetic, and the difference between the true bearing and magnetic bearing would be the variation.

Given:—Sun's altitude 36°, azimuth N. 40° E., object 73° to left of sun. Find the true bearing of the object and thence the variation, the magnetic bearing of the object being N. 20 W.

Sun's true bearing from azimuth tables -	N. 40 E.	(N A)
Arc A B calculated from arcs A X and B X	70	(A B)
True bearing of object B - - - - -	N. 30 W.	(N B)
Magnetic bearing of object B - - -	N. 20 W.	(M B)
Variation	10 W.	(N M)

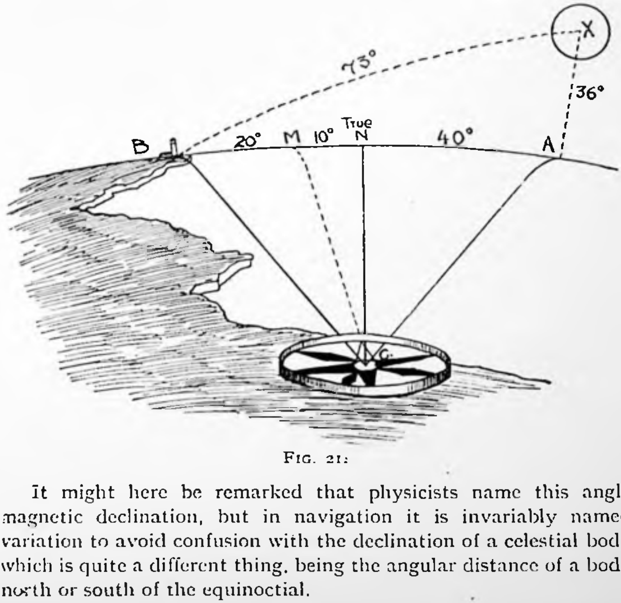


FIG. 21.

It might here be remarked that physicists name this angle magnetic declination, but in navigation it is invariably named variation to avoid confusion with the declination of a celestial body which is quite a different thing, being the angular distance of a body north or south of the equinoctial.

Finding variation at sea.—The approximate variation may also be found at sea by "swinging" ship, that is, turning her round in a circle and observing the bearing of the sun by the compass as her head is steadied on equi-distant points, say every fourth point. The difference between the compass bearing and the true bearing as obtained from azimuth tables gives the error of the compass for the direction of the ship's head at the time. The mean of all the errors found on equi-distant

points during a complete round turn is the variation for that particular geographical position. This method is based on the assumption that the sum of the east deviations is equal to the sum of the west deviations for a complete swing. This is probably the case in a wood ship, or composite ship, and even at a well placed compass mounted high above the hull in an iron ship, indeed, much of the information from which the Admiralty variation chart is compiled has been obtained by swinging ships at sea.

The whole operation might best be illustrated by means of the following table keeping in mind always that the

$$\text{error} = \text{var.} + \text{or} - \text{dev.},$$

also the empirical rule, that the error is named east when the true bearing lies to the right of the compass bearing, and west when it lies to the left.

Ship's head	Compass bearing of sun	True bearing of sun	Error of compass
N.	S. 14° E.	S. 40° E.	26° W.
N.E.	S. 15 E.	S. 38 E.	23 W.
E.	S. 17 E.	S. 36 E.	19 W.
S.E.	S. 18 E.	S. 34 E.	16 W.
S.	S. 18 E.	S. 32 E.	14 W.
S.W.	S. 13 E.	S. 30 E.	17 W.
W.	S. 7 E.	S. 28 E.	21 W.
N.W.	S. 2 E.	S. 26 E.	24 W.
			8)160
		Variation	20 W.

Variation at sea could also be found by placing a good compass in the ship's boat, which, being built of wood and copper, would be non-magnetic, and if the sea were smooth enough, launch the boat and pull away from the ship a short distance. The bearing of the sun by compass would be the magnetic bearing, and the difference between this magnetic bearing and its true bearing as got from the azimuth tables would be the variation approximately.

30. **Diurnal Changes of Variation.**—Experiments have shown that the normal direction of the magnetic needle undergoes small daily movements in addition to gradually changing its direction over a long period of years. About 8 a.m it points about 14′ to the east of

north ; at 1 p.m. a little to the west. It then returns to the east till midnight, when it makes another excursion to the west, returning to its original position about 8 o'clock in the morning. This angular deflection is greater in the day than in the night and in summer than in winter. These perturbations are small and do not enter into the practical aspect of compass work, but are mentioned here to emphasise the subtleties of magnetism and the extreme sensitiveness of the needle.

31. Irregular Magnetic Disturbances.—The needle is also subject to irregular disturbances due probably to electrical currents in the earth and in the atmosphere, as they are usually associated with Aurora Borealis. The compass card has been known to be sensibly deflected thereby, especially in high latitudes.

That the aurora is associated with atmospheric electricity is evidenced by the fact that magnetic storms always accompany it and that the auroral rays of light converge towards the direction in which the dipping needle points. No theory has, so far, been evolved which explains satisfactorily the surprising changes which take place in the earth's magnetic field and which, obviously, produce the peculiar secular and diurnal changes in the magnetic variation, and also the irregularly recurring magnetic storms such as the aurora, nor is there an accepted theory of the origin of atmospheric electricity, not even a satisfactory explanation of the cause of a thunder storm.

32. Local Attraction.—The most important source of irregular disturbance is that due to local magnetic attraction, and mariners are officially warned that " in some parts of the world there are depths of water sufficient for the largest ships to navigate in safety where the bottom is sufficiently magnetic and close enough to affect their compasses. Increased vigilance should be exercised when approaching those countries at night or in thick weather. The following places are known to be so affected:—Shetland Isles—West Coast of Scotland—Lough Larne approach—Gulf of Bothnia—Iceland—Odessa Bay—Isle de Los, W. Coast of Africa—Coasts of Madagascar—Tumboro Volcano and Sumbawa Island in Java—Cossack in North Australia—Fundy Bay and Cape St. Francis, Labrador. Other parts of the globe are suspected of similar disturbing effects, and all those experiencing it should on the spot determine its locality and report about it as they would any other hidden danger."

33. To Avoid Reiteration.—Where reference is hereafter made to the equator and the poles it is to be understood, unless otherwise stated, that the magnetic equator and the magnetic poles are referred to.

34. Magnetic Intensity.—The amount of the earth's magnetic force, when measured in the direction taken up by the needle when freely suspended at its centre of gravity, is called its magnetic intensity.

The value of the earth's total force is least in the vicinity of the equator, then increasing with the latitude is greatest near the poles.

The total force is resolved into the two components, horizontal force and vertical force, and these two forces also vary with change of latitude, their relative values depending on the angle which the lines of force make with the plane of the horizon.

35. Horizontal and Vertical Force.—At the equator the whole force is horizontal, but at the poles the whole force is vertical, and in any other latitude the earth's force is partly horizontal and partly vertical, the one component increasing while the other is decreasing, so that a gain in the value of one of them means a loss in the value of the other.

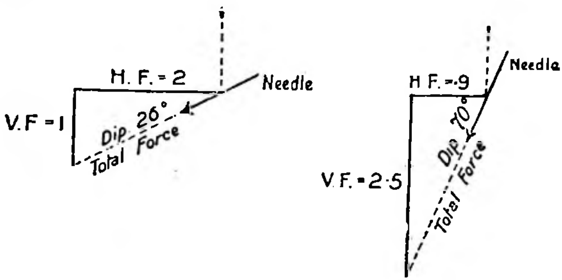


FIG. 22

BOMBAY.		GLASGOW.	
Horizontal force	= 2	Horizontal force	= ·9
Vertical force	= 1	Vertical force	= 2·5
Dip	= 26°	Dip	= 70°

36. A Trigonometrical Connection.—This general statement is more accurately expressed by the following equations :—

I.—Horizontal force = total force × cosine dip.

II.—Vertical force = total force × sine dip.

Keeping in mind that the value of cos. $0° = 1$ and cos. $90° = 0$, let us apply Equation I. to the following extreme cases. At the equator the magnetic needle is horizontal, therefore the dip is 0°. But cos. $0° = 1$, and by substituting this value in Equation I. we find that—

Horizontal force = total force × cos. 0°.
" = total force × 1.
∴ " = total force, when the magnetic latitude is 0°

The dip at the poles is 90°, but cos. $90° = 0$, and by substituting this value Equation I. now becomes

Horizontal force = total force × cos. 90°.
" = total force × 0.
∴ " = 0, when the magnetic latitude is 90°.

Of these two components, the horizontal one is the more important in navigation, as the directive power of the compass needle depends on the value of the earth's horizontal force. Fig. 22 exhibits the relative values of the two components of the earth's force at Bombay and Glasgow as given in Charts II. and III.

37. The Directive Force of the Compass.—The foregoing equation demonstrates that the horizontal directive force acting on the compass is greatest at the equator, and zero at the poles.

Another way of realising this important point is to remember that the needle, in obedience to the demands of the earth's force, is trying to settle itself in the same direction as the lines of force (*see* fig. 19). If it were able to do so at the poles the needle would stand vertical and tip the card up on its edge. But the weight of the card and its mountings coerces the needle into a horizontal position at the expense of directive power, hence the reason why compasses are sluggish in high latitudes, and when near the poles they may be affected so seriously as to become useless.

38. Vertical Force does not cause Deviation.—The vertical component, as already stated, is not so important, because a force acting in the vertical plane passing through the compass needle does not deflect it to the right or left.

$$\text{III.}\quad \frac{\text{Vertical force}}{\text{Horizontal force}} = \text{tangent dip.}$$

If the value of any two of these factors be known the third may be found by Equation III.; and a knowledge of their relative values in

different latitudes is important, as it enables the navigator to estimate the changes that may be expected in the magnetic condition of his ship and the probable change of deviation arising therefrom.

Charts showing curves of variation, dip, and horizontal force are given at the end of the book.

QUESTIONS.

1. Describe an artificial magnet and how a steel bar or needle is usually magnetised. (15) (19) also 93, Chapter VIII.

2. Which end of the compass needle or a magnet is commonly termed the red and which the blue pole? (16)

3. What is meant by the "field" of a magnet, and what is the law of inverse squares? (21-22)

4. What effect has the pole of one magnet of either name on the pole of the same name of another magnet, and what would be the consequence of the pole of one magnet of either name being brought near enough to affect the pole of contrary name if in these cases both magnets were freely suspended? (23)

5. The earth being regarded as a magnet, describe its effect on a magnetic bar or needle, freely suspended, but by the weight or by the nature of its mounting, constrained to preserve a horizontal position; and what would be the result if so mounted but free to move in every direction? (24)

6. Which is the red magnetic pole of the earth and which the blue, and give their geographical positions? (24)

7. Does the magnetic equator coincide with the geographical equator, if not, state clearly how it is situated. (25)

8. What is the cause of variation of the compass? (26)

9. What is meant by the term "local attraction"? Under what circumstances have ship's compasses been found to be affected by it, and name some of the localities in different parts of the world where this disturbance is to be found. (32)

10. Describe the meaning of the term "horizontal force" of the earth; where is it greatest and where least, and what effect has it in respect to the increase or decrease of the directive force of the compass needle? (36) (37)

11. Where can the values of the magnetic dip, the earth's horizontal force, and the variation be found? (38)

12. State in what parts of the globe lying in the usual tracks of navigation the variation changes rapidly, and what special precaution should be observed when navigating these localities; also why a "variation" chart is then very useful? (29)

13. Why is a knowledge of the magnetic dip, and the earth's horizontal force important in dealing with compass deviation ? (38)

14. Describe the meaning of the term "vertical force" of the earth; where is it greatest and where least ? (36) (37) (38)

15. Would you expect a compass to be more seriously affected by any given disturbing force when near the magnetic equator or near the poles ? And state the reason. (37)

16. What effect has heat on a magnet ? (20)

17. What is meant by the "law of inverse squares" ? (22)

18. When is a magnet said to be "end on" and "broadside on" ? and how does its effect on the compass differ when in these positions ? (22)

19. How may the magnetic variation be found (*a*) on shore, (*b*) at sea? (29)

20. Describe an electro magnet and how a steel bar may be magnetised by it (page 138)

21. What precautions should be taken when loading or discharging a cargo of iron with an electro magnetic crane? (page 139)

CHAPTER III

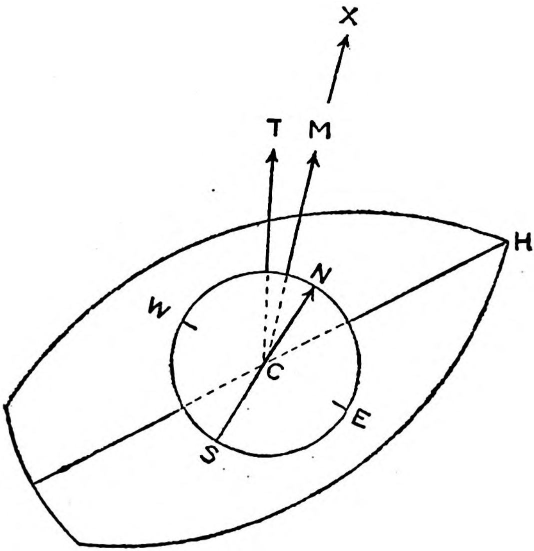


Fig. 23.

39. In fig. 23, *C T* represents the true meridian
C M the magnetic meridian
C N the compass north
C H the ship's head
N E S W the compass.

Angle *T C M*, **the variation**, is the angle contained between the true and magnetic meridians. Var. $=10°$ E. in diagram.

Angle *M C N*, **the deviation**, is the angle between the magnetic meridian and the compass needle. Dev. $=20°$ E. in diagram.

Angle $N C H$, **the compass course**, is the angle between the direction of the compass needle and the ship's head. N. 30° E in diagram.

Angle $M C H$, **the magnetic course**, is the angle between the magnetic meridian and the ship's head. N. 50° E. in diagram.

Angle $T C H$, **the true course**, is the angle between the true meridian and the ship's head. N. 60° E. in diagram.

Compass course	N. 30° E.
Deviation	20 E.
Magnetic course	N. 50 E.
Variation	10 E.
True course	N. 60 E.

40. Rules for naming Deviation.—Deviation is caused by the magnetic condition of the ship, her equipment and cargo. It is named east when the compass north is deflected to the right of the magnetic meridian, and west when deflected to the left.

The deviation alters with every new direction given to the ship's head, it is necessary therefore to find the amount for each course by steadying the ship's head on successive points and noting the angle between the known magnetic bearing of a distant object and its bearing by compass. The deviation is named east when the magnetic bearing lies to the right of the compass bearing and west when to the left.

In fig. 23, the compass north is deflected 20° to the right of magnetic north, hence the deviation is east. If X be the direction of a distant object then its magnetic bearing is N. and its compass bearing N. 20° W., the deviation is east, because the magnetic bearing of the object lies to the right of its bearing by compass.

41. Chaos.—The total magnetic force of a ship is made up of innumerable magnets. Every rivet, bolt, beam, pillar and plate is a magnet, and each exerts its own particular influence on the needle depending on its position and distance from the compass. The result is that the ship is an irregular and unstable magnet. The needle is attracted simultaneously towards the bow, stern, port side, starboard side, downwards and upwards, by this multitude of magnets, but eventually it comes to rest in a direction depending on the resultant effect of these conflicting forces.

42. Order Restored.—Happily order can be restored by resolving the total deviation into the following components and treating each separately :—

I. The deviation arising from sub-permanent magnetism, that is the more stable part of the ship's magnetism, which is located principally in the shell plating. Its effect can be illustrated by conceiving a huge magnet placed inside the hull in a definite position depending on the direction the ship's head occupied in the building yard.

II. The deviation produced by transient induced magnetism in vertical bars.

III. The deviation produced by transient induced magnetism in horizontal bars.

IV. The vertical component of the ship's force which only causes deviation when the ship heels.

There are two types of magnetism to consider, transient induced and sub-permanent.

43. Transient Induced Magnetism.—Transient induced is the name given to the magnetism imparted by the earth's force. A red pole is generated in that end of the bar which is directed towards the north and, of course, a blue pole in the other end. The magnetism is transient in character because the distribution and the amount of polarity in the bar changes when the position of the bar is altered with respect to the earth's lines of force.

44. A Demonstration.—An artificial magnet also generates transient induced magnetism within the limits of its field.

Place iron filings in a glass test tube. Hold the tube close to the compass. Note that the needle does not respond.

Draw the *blue* pole of a magnet from the mouth to the bottom of the tube. Hold the bottom of the tube close to the compass. Note that the north point is repelled. This indicates a red pole at the bottom of the tube, because *red repels north*. The *blue* pole of the magnet has induced *red* polarity in the filings. Shake the tube and again hold it close to the compass needle ; no effect. The magnetism has vanished ; it is transient.

Draw the *red* pole of the magnet along the tube from the mouth to the bottom. Observe how the filings bristle up and then settle down. Again hold the bottom of the tube close to the compass.

Note that the north point is now attracted. The *red* pole of the magnet has induced *blue* polarity in the filings. Shake the tube and once more hold it close to the compass ; it has no effect on the needle. The second dose of induced magnetism has also vanished.

45. The Molecular Theory of Magnetism offers an explanation of this phenomenon. Each tiny filing is a magnet. When the tube is shaken the filings are all topsy-turvy, red and blue poles pointing in every direction, thus neutralising their magnetic effect. When the magnet is drawn along the tube the filings are stimulated into action and all arrange themselves in a definite direction, their red poles one way and their blue poles the opposite way, the combination of the whole mass of filings thus producing temporarily the effect of a magnet having a red pole at one end of the tube and a blue pole at the other end.

46. Another Demonstration.—The earth magnetises a bar of iron in a manner similar to that witnessed in the iron filings. Hold a poker in the line of dip (par. 24) and place the lower end (the point) close to the compass—note that the compass north is repelled, thus revealing the existence of a red pole at the point of the poker. Turn the poker end for end, and note that the lower end (the handle now) also repels the compass north, thus demonstrating that the red pole is generated in that end directed towards the north. Hold the poker at right angles to the line of dip, it has no effect on the needle—it is neutral—because the earth's lines of force are now passing crosswise, instead of longitudinally, through the bar. The distribution of polarity in a bar is dependent on its position relatively to the line of dip. The magnetism in the poker is transient induced.

47. " Soft " and " Hard " Iron.—Some qualities of iron are more susceptible to induction than others.

Soft iron is the name given to that quality which freely changes its polarity with change of position, and instantly loses its magnetism when removed out of the field of the inducing magnet.

Hard iron is more difficult to magnetise, but when acquired it has the power of retaining its magnetism more or less permanently.

Vertical and horizontal bars partake more of the nature of soft iron than of hard, while the shell plating of a ship appears to approach more closely to the hard iron type.

Steel can be manufactured to almost any desired quality, the

degree of strength being determined mainly by the percentage of carbon added to the iron. Lloyd's tests for the mild steel used in ship construction are designed to arrive at the quality of the steel as regards its ductility, flexibility and strength. The brittleness and, in some respects, the strength of steel increase as the percentage of carbon increases but at the same time it loses ductility, hence the reason why the tests for frames and plating and parts which are to be subjected to much bending differ somewhat from the tests applied to stern posts, keels and other more rigid members of the hull. The more carbon introduced into the iron when it is being manufactured into steel the more brittle will the finished product be. Cast iron, for example, contains from 2 to 5 per cent. of carbon, but the steel used in ship work contains from about 2 per cent. in the mild quality to about 4 per cent. in high tensile steel. But the quality of the steel also determines its magnetic susceptibility, and as various grades of steel enter into the construction of a ship, it follows that the magnetic permeability of the several members will vary in degree between that of the docile and unresisting " soft " iron to that of the stubborn resistance to magnetisation offered by " hard " iron.

The inductive capacity of soft iron is increased when the iron is heated, but if its temperature be raised to a critical point, about 780° C, it becomes non-magnetic and no longer possesses the property of being magnetised. This may be tested by heating an iron nail to bright redness, and while still hot, touching it with the pole of a magnet and repeating contact while the iron is cooling. The nail is not attracted in the least until it has considerably cooled, when it suddenly reacquires the property of being attracted by the magnet.

48. Converting Induced into Sub-permanent Magnetism.—Take the poker, again hold it in the line of dip and close to the compass. A red pole is generated in the lower end (the point) and a blue pole in the upper end (the handle). Give it a few sharp blows with a hammer—the vibration stimulates the molecules of the iron into greater activity, especially the sluggish ones, they straighten out and arrange themselves parallel to each other like the filings in the test tube—the induced magnetism thus becomes intensified. Turn the poker end for end, the handle now being downwards—it attracts the needle—the handle has retained the original blue pole, instead of changing into a red pole as demonstrated in par. 46.

The hammering has altered the magnetic condition of the poker, which has now acquired, temporarily, the properties of a permanent magnet. The transient induced magnetism has been converted into sub-permanent, " sub " because the poker will in time lose the greater part, if not the whole, of this magnetism.

49. **How a Ship is Magnetised.**—A ship, like the poker, is first magnetised by induction from the earth, her magnetic poles being located in the line of dip, red polarity appearing in that part of the ship which is presented towards the north and blue polarity in the part presented to the south. With the incessant hammering she undergoes during construction these poles become permanently fixed, and although their intensity rapidly diminishes, especially during her first voyage, yet a very appreciable amount of this sub-permanent magnetism remains during the whole period of the ship's existence; indeed, it is this component of her magnetic force which usually produces the greater part of the total deviation appearing on the compass.

50. **The Distribution of the Polarity** in a ship is governed by the geographical position of the building yard and the direction of the ship's head on the stocks. Fig. 24 represents the earth magnet, with lines of force passing through five ships, heading north in imaginary building yards.

A and *E* are two ships built respectively at the north and south poles, where the dip is 90°. The lines of force pass vertically through them, a red pole appearing on the under side of *A* and a blue pole on the under side of *E*.

C represents a ship built at the equator where the dip is 0°. The lines of force pass horizontally through the ship, the forward half being flooded with red polarity and the after half with blue.

B and *D* are two ships built respectively in the north and south hemispheres, at places where the dip is about 70°, the Clyde and Tasmania, for example.

The sub-permanent poles are always situated in the plane of the dip needle, blue uppermost in the N. hemisphere and red uppermost in the S. hemisphere, but in this case the lines of force pass obliquely through the ship, so that in the Clyde built vessel (*B*) the blue polarity is in the after upper end of the ship, whilst in the Tasmanian vessel (*D*) the blue polarity is in the after lower part of the ship.

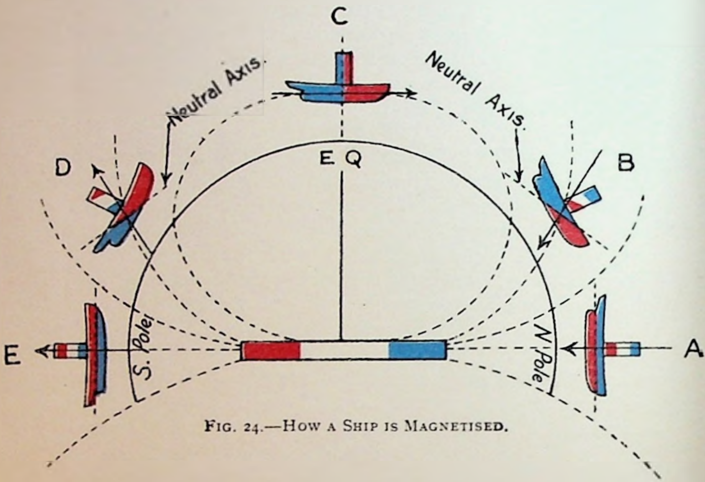


FIG. 24.—HOW A SHIP IS MAGNETISED.

This distribution, of course, only applies to cases where the ship's head has been north whilst building.

51. Unloading Superfluous Magnetism.—The intensity of the ship's magnetic force undergoes considerable reduction, especially during her first voyage, but after a time it settles down to a fair degree of permanency. With a view to getting rid of as much as possible of the unstable part of the magnetism before adjusting the compass of a new ship, it is desirable that her head, when she is being fitted out, should be in the opposite direction to what it was on the building slip.

This superimposes an induced pole of an opposite name, on the original polarity of the ship, thereby decreasing her magnetic intensity, and this natural process of eliminating the less tenacious part of the sub-permanent magnetism is accelerated by the vibration and concussion to which the ship is subjected during the fitting out period.

The sub-permanent force of the ship is resolved into two parts—a horizontal component which produces deviation, and a vertical component which causes an error when the ship heels over only. We shall now proceed to discuss the horizontal component.

QUESTIONS.

1. What is meant by transient induced magnetism ? (43)

2. What do you understand by the terms "soft" iron and "hard" iron, and what are their respective properties as regards acquiring and retaining magnetism ? (47)

3. Describe what is usually termed the sub-permanent magnetism of a ship, state when and how it is acquired, how the poles are located, and why it is called sub-permanent magnetism. (49) (50)

4. State the rules for determining whether deviation is easterly or westerly. (40)

5. Before adjusting the compasses of an iron ship what is it desirable to do with the view to eliminating as far as possible what may be termed the unstable part of the ship's magnetism ? (51)

6. Explain the molecular theory of magnetism. (45) (page 192).

7. What effect has heat on the inductive capacity of soft iron ? (47)

8. Describe how a ship is magnetised when built in Great Britain. (fig 24 B)

EARTH'S NORTH. MAGNETIC POLE.

CHAPTER IV.

52. The Sub-permanent Poles are located in the plane of the magnetic meridian passing through the ship when she is being built.

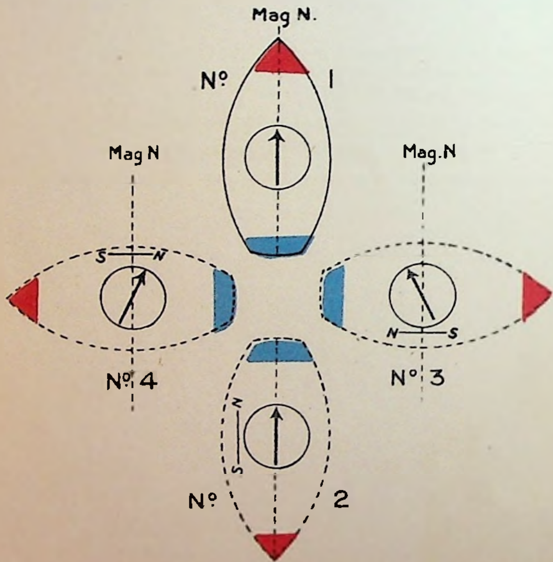


FIG. 25.—CO-EFF – B.

53. Head North when Building.—Assuming head north (magnetic) on the stocks, the poles would be in the fore and aft line, red at the bow and blue at the stern, as in fig. 25, ship No. 1.

When swung for deviation the needle—and by needle is meant the compass north which is always a red pole—is attracted towards the stern, but no deviation appears when the ship's head is north (No. 1) or south (No. 2); because the poles (as seen in fig. 25) are then acting

in a line with the needle. On easterly courses the deviation is west, the compass north being deflected to the left of magnetic north (No. 3), and on westerly courses the deviation is east, the compass north being now deflected to the right (No. 4).

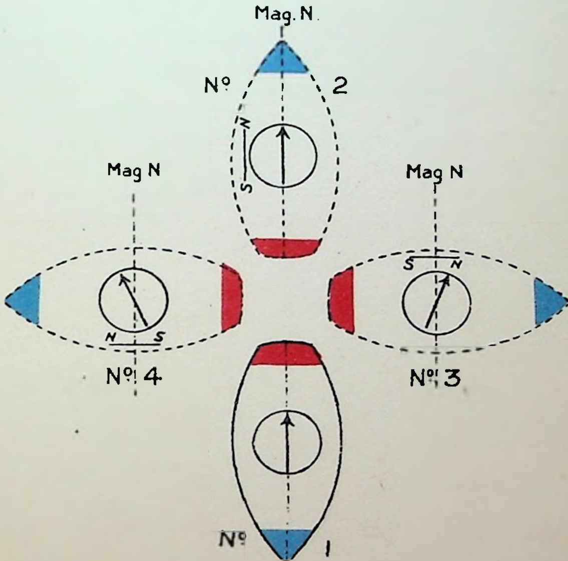


FIG. 26.—CO-EFF. + B.

54. Head South when Building.—Had the ship's head been south in building yard as in fig. 26, ship No. 1, the poles would still be in the fore and aft line, red at the stern, and blue at the bow, the needle being attracted towards the latter; no deviation would appear when the ship's head is steadied on north or south (No. 1 and 2), but the needle would be deflected to the right when heading on easterly courses (No. 3), and to the left when on westerly courses (No. 4).

55. Co-efficient B.—This deviation is summed up as co-efficient

B. the fore and aft component of semi-circular deviation, caused by sub-permanent magnetism.

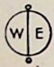
The deviation is greatest when the ship's head is E. and W. magnetic, decreasing to zero on the N. and S. points.

$+B$ represents an attraction to the bow.

$-B$ an attraction to the stern.

$+B$ gives E. dev. on easterly courses and W. dev. on westerly courses.

$-B$ gives deviation of an opposite name.

Co-eff. $+B$. 

Co-eff. $-B$. 

This fore and aft force is compensated by placing a magnet fore and aft with its north end aft for $-B$, as in fig. 25, but its north

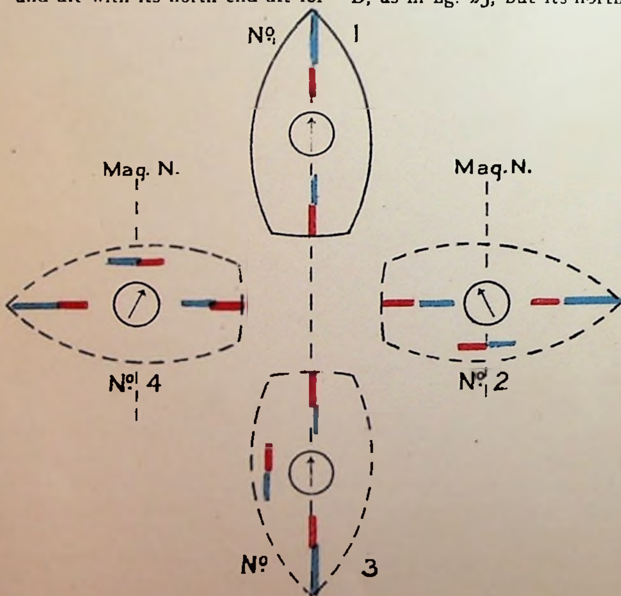


FIG. 27.

SWINGING DEVIASCOPE. CO-EFF. $-B$. HEAD BUILT NORTH.

end forward for $+B$, as in fig. 26, and moving the magnet towards the compass until the needle points north magnetic, the ship's head being steadied temporarily for the purpose on east magnetic or west magnetic, the maximum deviation then produced being a measure of the intensity of the horizontal component of the ship's magnetism acting in the fore and aft vertical plane passing through the compass.

A co-efficient B is produced at the deviascope by placing two small magnets end on to the compass in the fore and aft midship deck line of the model, one before and one abaft the compass.

If it is desired to produce an attraction towards the stern ($-B$ due to the ship's head having been north in building yard) the south (blue) pole of the after magnet and the north (red) pole of the forward magnet are, respectively, kept next to the compass as this arrangement places the compass between a blue pole at the stern and a red pole at the bow, as will be noted on referring to fig. 27. The influence of the remote poles of the magnets only modifies, but does not equal, that of the near poles, the result on the compass being one of action between the near ends only. By turning the two small magnets end for end, so that the blue pole of the forward one and the red pole of the after one are now next the compass, the effect of an attraction towards the bow ($+B$, due to the ship's head having been south in building yard) is produced.

A similar effect could be obtained by placing a long single magnet below, or above, the level of the compass, with its poles equi-distant from the centre of the needle and in the fore and aft line of the model (fig. 28), the blue pole aft if it is desired to demonstrate the effect of $-B$, (attraction to the stern), but the blue pole forward if a $+B$ (an attraction to the bow) is desired. The adoption of two small magnets to represent the influence of sub-permanent magnetism has advantages over the use of a long single magnet, the most obvious being that small magnets are more convenient to handle, and the amount of deviation may be readily increased, or decreased, by simply moving them closer to, or away from, the compass. Care should be taken, however, that the small magnets are of equal power and placed at an equal distance from the centre of the compass. A series of concentric circles scored out on the deck of the model one inch apart, and having their common centre at the intersection of the fore and aft and athwartship deck lines, facilitates the placing of the magnets at any desired distance.

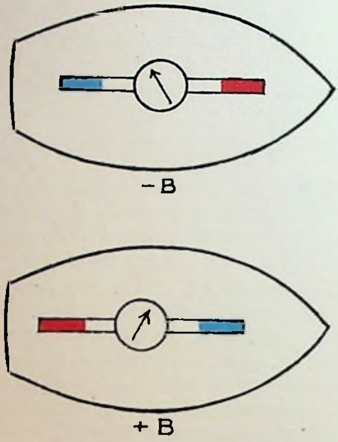


FIG. 28.—ILLUSTRATING CO-EFF. B WITH A SINGLE MAGNET.

The small magnets having been placed in position to produce a $-B$, it will be remarked, when the ship's head is on north or south (fig. 27, Nos. 1 and 3), that (1) the vertical fore and aft plane of the ship, (2) the longitudinal axis of the needle and (3) the magnetic meridian, are all in a line so that no deviation is produced. Turn ship's head to east (No. 2), the magnetic axis of the ship, that is the line joining her sub-permanent poles, is now at right angles to the axis of the needle thus exercising on it a mechanical couple which turns the north of the compass towards the stern, a west deviation, because the compass north lies to the left of magnetic north. The fore and aft compensating magnet shown on the starboard side of No. 2 may now be placed in position and moved in towards the compass until the needle again lies in the plane of the magnetic meridian.

Finally, turn ship's head to west (No. 4), no deviation should appear because the red and blue poles of the compensating magnet are, respectively, adjacent to the blue and red poles of the sub-permanent magnets, the magnetic action of the whole combination being to create a neutral field at the position occupied by the compass.

Refer to fig. 29 which is intended to illustrate how the lines of force emanating from the fore and aft magnets X and Y, and from the compensating magnet Z, are presumed to exercise their influence on the magnetic particle N situated at the centre of the needle, or

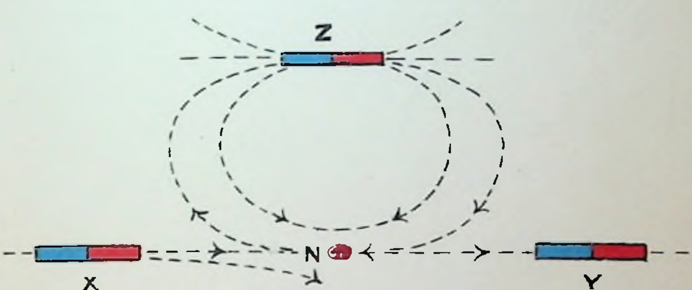


Fig. 29.

system of needles if two or more are placed on each side of the centre of the card. The lines of force are conceived to flow from the north to the south poles of a magnet, that is from the red to the blue poles. It will be noted that the line of force flowing from X to Y passes from left to right through N, and that the line of force flowing from the magnet Z passes from right to left through N, in exactly the opposite direction, and these two forces acting on the particle N being equal and opposite, they, mechanically speaking, counteract each other so that the needle is free, so far as these two forces are concerned, to again lie in the plane of the magnetic meridian.

This diagram also illustrates the importance of a short compass needle, for if it were long it would lie in a distorted field, because some of the lines of force from magnet Z might act on the north end of the needle, and some from magnet X might act on the south end, thus setting up a couple which would turn the needle to the left. The length of the needle, so far as compass adjustment is concerned, is purposely made so short as to be negligible.

The semi-circular deviation due to the fore and aft force increases by gradual increments as the ship's head is turned away from north and south, attains its maximum when heading east and west, and gradually decreases again to zero on north and south. The deviation

may be represented in graphical form as in fig. 30, where the vertical line represents the rim of a compass card straightened out, each point of the compass being called an abscissa. Lines (ordinates) are laid off from equi-distant points at right angles to the vertical line and each ordinate is made equal in length to the number of degrees

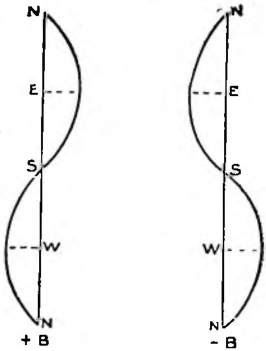


FIG. 30.

of deviation on its particular point, the length being measured from any convenient scale of equal parts. A curve is then drawn through the extremities of the ordinates, and the sinuous curve thus formed is called a sine curve, because it is zero when the angle is 0° and a maximum when the angle is 90°, just as in trigonometry, Sine 0°=0 and sine 90°=1. The deviation due to this force varies as the sine of the course, or azimuth of ship's head, the trigonometrical expression being, dev.$=B\times$sine co., where B is the maximum value of co-efficient B, and co. is the direction of the ship's head.

EXAMPLE:—The value of B when ship's head is east being 12°, find value of B when heading N. 30° E.

Dev. $=B\times$sin. co.

$=12^\circ\times$sin. 30°

$=12^\circ\times.5$ (*see* Table of Natural Sines, etc.).

$=6^\circ$ on N. 30° E.

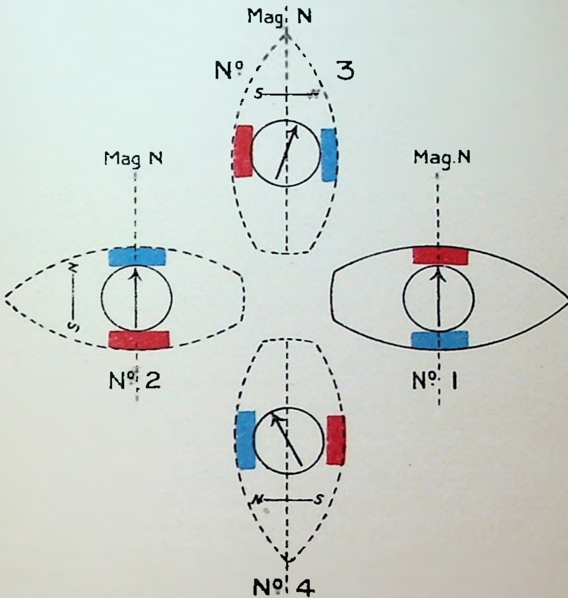


FIG. 31.

56. Head East when Building.—The following features appear when the ship's head has been east whilst building, as in fig. 31 (No. 1). Red polarity is generated on the port side, and blue on the starboard side towards which the compass needle is attracted. No deviation is caused when the ship's head is east or west, ships Nos. 1 and 2, but an E. dev. appears when heading north (No. 3) and a W. dev. when heading south (No. 4). Had the ship's head been west in building yard instead of east, red polarity would have appeared to starboard and blue to port, causing an attraction of the needle to the port side of the vessel, and producing a deviation of contrary name to that shown in fig. 31.

57. Co-efficient C.—This is all represented by co-efficient *C*, the athwartship component of semi-circular deviation due to sub

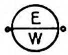
permanent magnetism, the deviation being greatest when the ship's head is N. and S. magnetic, decreasing to zero on the E. and W. points.

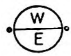
$+C$ represents an attraction to starboard.

$-C$ to port.

$+C$ gives E. dev. on northerly courses and W. dev. on southerly courses.

$-C$ gives deviations of an opposite name.

Co-eff. $+C$ 

Co-eff. $-C$. 

This athwartship force is compensated by a magnet placed athwartships, as shown in fig. 31, with its north end to starboard for $+C$ but to port for $-C$, and moving the magnet towards the compass until the needle points north magnetic, the ship's head being steadied temporarily on north or south magnetic as the maximum deviation then produced is a measure of the intensity of the ship's magnetism in the athwartship vertical plane passing through the compass.

To demonstrate a co-efficient C on the deviascope the two small magnets to represent the influence of sub-permanent magnetism are placed on the athwartship deck line of the model, end on to the compass, and if it is desired to produce a $-C$ (ship's head west in building yard) fig. 32, No. 1, the red pole of the starboard magnet and the blue pole of the port one, are kept next to the compass thus causing the needle to lie between a red pole to starboard, and a blue pole to port towards which the north end of the needle will be attracted. It will be noted in No. 1 that the poles of the ship and the longitudinal axis of the needle are in the plane of the magnetic meridian, and no deviation appears. But when the head of the model is turned to north magnetic (No. 2), the poles of the ship are now seen to have swung out at right angles to the axis of the needle, the north is deflected to the port side of the ship, that is to the left of the magnetic meridian, thus producing west deviation. The athwartship compensating magnet, shown abaft the compass, may now be placed in position and moved in towards the compass until the needle again points north magnetic. When heading east (No. 3) no deviation is produced. On swinging head to south magnetic (No. 4) no deviation should appear, as the athwartship compensating magnet is deflecting the needle just as many degrees to starboard as

the sub-permanent magnets are deflecting it to port. Take away the compensating magnet and an east deviation will appear.

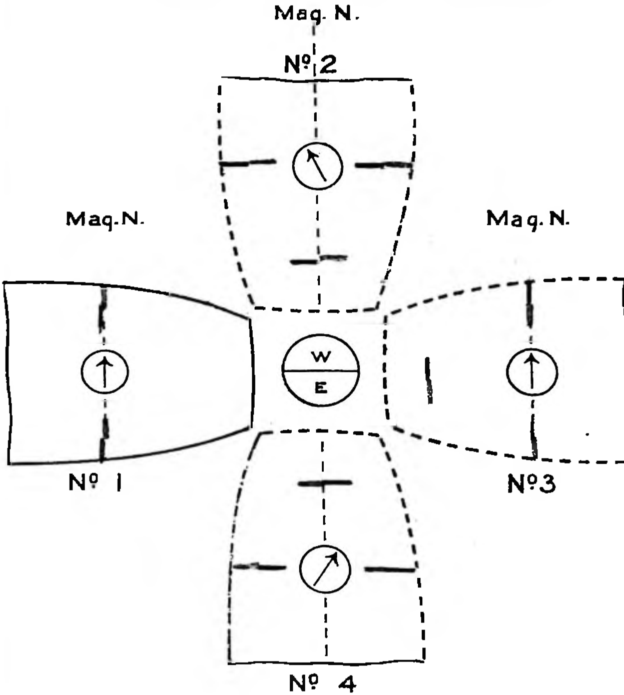


FIG. 32.—SWINGING DEVIASCOPE. CO-EFF. $-C$. HEAD BUILT WEST.

A graphical representation of the swing curve for co-efficient C is given in fig. 33 from which it will be noted that the deviation varies as the cosine of the course, because cos. $0°=1$ and cos. $90°=0$; in other words, it is a maximum on north and south, and zero on east and west, the trigonometrical expression being dev.$=C \times$cos. co. where C is the maximum value of co-efficient C, and co. is the direction of the ship's head.

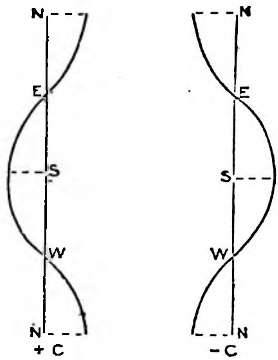


FIG. 33.

EXAMPLE :—The value of C when heading north being 10°, find value of C when heading N. 30° E.

$$\begin{aligned} \text{Dev.} &= C \times \text{cos. co.} \\ &= 10^\circ \times \text{cos. } 30^\circ \\ &= 10^\circ \times \cdot 866. \\ &= 8\cdot 66^\circ \text{ on N. } 30^\circ \text{ E.} \end{aligned}$$

58. The Co-efficients and Ship's Head whilst Building.—It is obvious from figs. 25 to 32 that the co-efficients indicate the quadrant of the compass in which the ship was heading when on the stocks.

$+B$	indicates head	southerly.
$-B$	,,	northerly.
$+C$	,,	easterly.
$-C$	,,	westerly.

It will be observed, also, that no deviation appears when the ship's head happens to be in the same or in the opposite direction to what it was during the period of construction, and the maximum amount occurs when heading at right angles to this natal direction.

Although no deviation is apparent when the ship is on a course parallel to the direction of her building ways, yet the directive power of the needle is sensibly weakened when her head is in the same direction as it occupied during the period of her construction and strengthened when in the opposite direction, owing, in the former

case, to the ship's magnetism acting in opposition to the earth's force, and in the latter case, acting in combination with it.

For example, in fig. 25, (ship No. 1), the sub-permanent red pole at the bow is opposing the efforts of the earth's blue pole to direct the compass needle, but when the ship's head is slued to south, No. 2, the ship's blue pole at the stern combines with the earth's blue pole and so increases the directive force of the compass for the time being.

Let us discuss this a little more fully. Keep clearly in mind that the north end of the needle is red, and that the only natural source from which the compass derives its pointing power is the horizontal component of the earth's total magnetic force. Again refer to fig. 25 (No. 1), and imagine the earth's blue pole to be situated across the top of the page, we see the red sub-permanent pole of the ship, interposed between the controlling pole of the earth and the compass. The red pole of the ship magnet is weakening the directive force of the needle when heading in this direction, which note is the same as when being built. But when heading south (No. 2), we find the sub-permanent blue pole at the stern now interposed between the earth's blue pole and the compass. The ship magnet for this direction, which is now exactly opposite to the building yard, is allied to the earth's force; the two blue poles are acting in conjunction for the time being and the directive power of the needle is strengthened temporarily.

These are the two conditions under which the ship magnet exercises its greatest effect on the directional property of the needle, namely, when heading as in building yard, and, when heading in the opposite direction; in the former case its directive force is diminished and in the latter case increased. When the ship's head is at right angles to the building yard direction the magnetic axis of the ship is at right angles to the needle, and so the ship's lines of force do not influence its directive power, although for this direction the sub-permanent magnetism causes its maximum deviation.

The importance of a strong directive force at the compass is readily demonstrated at the deviascope by bringing the two small magnets representing sub-permanent magnetism in the fore and aft line of the ship (fig. 27), close up to the compass, then, when the head of the model is turned to south (No. 3) it will be found that the compass comes quickly to rest, the needle readily finds the north. But when the head of the model is turned to north the card is found to be sluggish, it is slow in finding the north, and it may be difficult,

if not impossible, to keep the north point of the card to the lubber line, because the natural property of the needle by which it points north has, in this case, been almost destroyed by the ship's sub-permanent magnetism being now antagonistic to the earth's force, and the compass would now be very easily deflected by any magnetic influence in its vicinity.

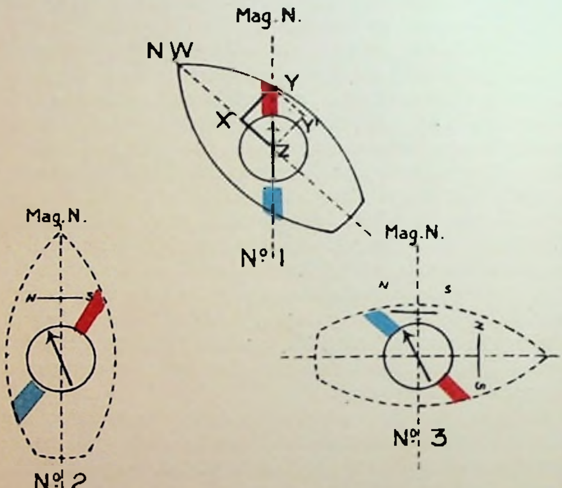


FIG 34.

59. Head N.W. whilst Building.—Suppose the ship's head had been N.W. whilst building, as in fig. 34, ship No. 1, a red sub-permanent pole would be fixed on the starboard bow and a blue on the port quarter. The magnetic axis of the ship would lie obliquely to the keel at an angle of 45°. The ship's force is now resolved into the fore and aft component co-efficient *B*, represented in magnitude by the line *Z X* in fig. 34, and the athwartship component, co-efficient *C*, represented by the line *X Y*.

60. Compensation of Semi-circular Deviation.—To compensate the compass proceed as follows :—

I. Steady the ship's head on *N*, magnetic, as in fig. 34, ship No. 2. The compass north is drawn to port, a *W* dev., co-eff. $-C$, caused by the athwartship component of sub-permanent magnetism. This deviation is corrected by placing a magnet athwartships having its north end on that side towards which the needle is drawn.

II. Steady the ship's head on *E*, magnetic, as in fig. 34, ship No. 3. The compass north is drawn aft, a *W* dev., co-eff. $-B$, caused by the fore and aft component of sub-permanent magnetism. It is corrected by a fore and aft magnet having its north pole at that end of the ship towards which the compass north is attracted.

The semi-circular deviation due to the permanent part of the ship's magnetism is now compensated. It is immaterial whether the ship's head is steadied on E. or W., or on N. or S., when correcting *B* and *C* respectively, and the order of correcting the co-efficients is that which is most convenient and expeditious when swinging ship.

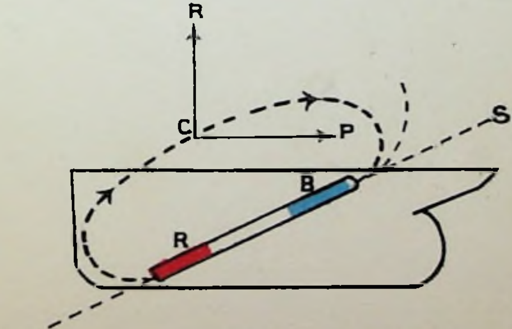


FIG. 35.—HEAD N. IN BUILDING YARD.

We have, so far, assumed the ship's magnetic axis to be lying in the same horizontal plane as the compass, and this would be true if the ship were merely a thin horizontal plate of iron having breadth and length, but practically no depth. The poles of the ship, however, are generated in the plane of the earth's line of force passing through the hull when she is on the stocks, so that her three dimensions,

length, breadth and depth, have to be taken into account. If, as in fig. 35, *N S* represents the line of dip passing through a ship in building yard, heading north, and *R B* the ship magnet, then the ship's line of force passes obliquely upwards at the compass (*C*). The obliquity of this line of action on the needle impels it upwards and towards the stern, the direction of this diagonal force being resolved into two parts (1) a vertical component (*R*), and (2) a horizontal component (*P*).

If, as in fig. 36, *N S* again represents the line of dip passing through a ship heading east on the stocks, then *R B*, the ship

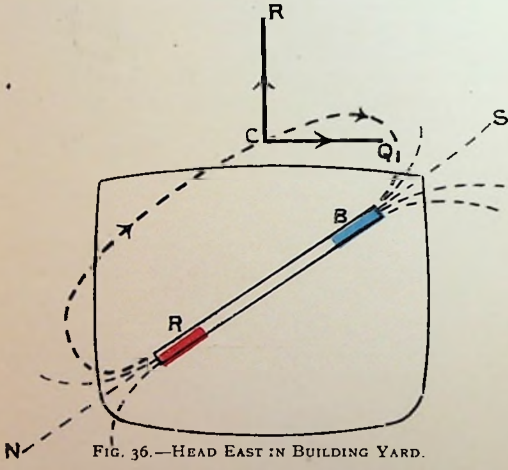


FIG. 36.—HEAD EAST IN BUILDING YARD.

magnet, would lie across the ship at a slope, depending on the angle of dip for the place, the red pole being somewhere about the port bilge and the blue pole near the starboard scuppers. The ship's line of force would pass obliquely upwards through the compass (*C*), the direction of this diagonal force being resolved into two parts (1) a vertical component (*R*), and (2) a horizontal component (*Q*) acting in the athwartship line.

When built heading in any direction, other than the cardinal points, the ship magnet lies askew in the hull and the line of force passes through the compass, not only more or less vertically but also

slantingly across the deck, so that the line of action is resolved into the three directions, P (fore and aft), Q (athwartships) and R (vertical) as indicated in fig. 37 where R B is intended for the line of dip

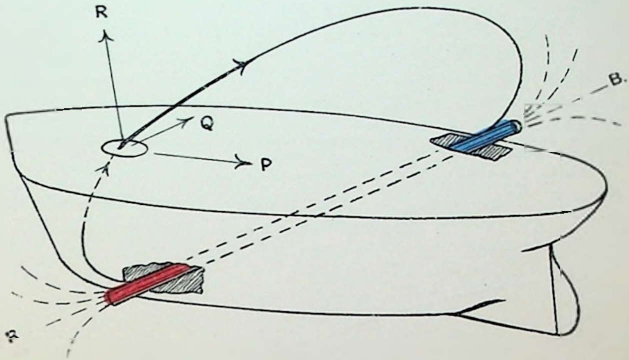


FIG. 37.—HEAD N.E. IN BUILDING YARD.

passing through a ship heading north-easterly on the stocks, and so bringing the red pole of the ship magnet low down on the port bow and the blue pole high up on the starboard quarter; the line of force in this case is flowing diagonally upwards through the compass from the port bow to the starboard quarter.

The letters P, Q, and R are adopted in the Admiralty Manual and other works which deal exhaustively with the theory underlying the deviation of the compass, and they are the conventional symbols used in mechanics to express mathematically the action of two or more forces acting on a point, the algebraic signs in this case being $+P$ to the bow, $-P$ to the stern, $+Q$ to starboard, $-Q$ to port, $+R$ downwards, and $-R$ upwards. One method, and it is a very practical and seamanlike method, of arriving at the relative values of these three forces is by noting the deviation produced on the compass, the value of co-efficient B being a measure of the ship's fore and aft magnetic force, and the value of co-efficient C a measure of her athwartship force. An indication of the intensity of her vertical force (R) is obtained by listing the ship to one side and taking note of the heeling error produced on the compass, or by means of the dip of a vertical force instrument.

61. The Parallelogram of Forces.—If two forces acting on the same particle be represented in magnitude and direction by two adjacent sides of a parallelogram drawn from their point of application, their resultant will be represented in magnitude and direction by the diagonal of the parallelogram drawn from that point.

The "composition" of forces is the name given to the methods of finding a single force called the "resultant" which is equivalent to two or more forces, such, for example, as determining the deviation of the compass, for a given direction of the ship's head, from the values of co-efficients A, B, C, D and E.

If the direction of a force acting on a particle be known, it may be resolved into several components; this is known as the resolution of forces, and the parallelogram of forces is a method by which it may be done. For example, figure 38 is a diagrammatic representation of

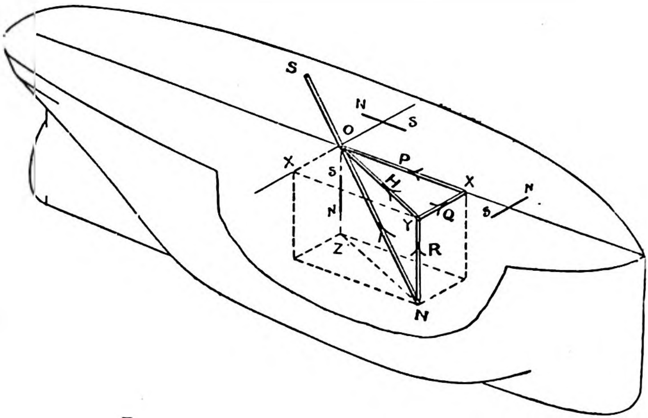


FIG. 38.—RESOLUTION OF SHIP'S MAGNETIC FORCE.

a ship whose head has been north-westerly in a building yard situated in a high north latitude, the sub-permanent force of the ship being represented by the magnet $S\ N$, having its north or red end at the starboard bow, which will repel the compass needle in the direction of $N\ O$.

The line $N\ O$ represents in direction and magnitude the effect of the ship's sub-permanent force, and this single force, which is the

diagonal of the parallelogram *O Y N Z* is resolved into vertical and horizontal components which are represented respectively by the adjacent sides *N Y* and *Y O* of the parallelogram. The vertical force, *R*, repels the north point of the compass upwards, and the horizontal force, *H*, repels it towards the port quarter of the ship. But this horizontal force, *H*, acts obliquely to the keel so, for the purposes of adjusting the compass, it is resolved into a fore and aft component *P* acting towards the stern, and an athwartship component *Q*, acting towards the port side, and the magnitude of these components is represented by the adjacent sides, *Y X* and *X O*, of the parallelogram *O X Y X*. Thus the force due to the sub-permanent magnetism acting on the compass is resolved into three components, a vertical force (*R*) which causes heeling error, a fore and aft force (*P*), and an athwartship force (*Q*), which cause deviations distinguished respectively by the symbols *B* and *C*.

It will be noted that half the parallelogram is sufficient, so that *N O Y* and *O X Y* are known as triangles of forces.

In fig. 34, No. 1, the diagonal *Z Y* represents the direction and magnitude of the ship's sub-permanent force, *X Y* or $Z\ Y^1$, the athwartship component of that force, co-efficient *C*, and *Z X* or $Y\ Y^1$ the fore and aft component, co-efficient *B*, the former being compensated with an athwartship magnet and the latter with a fore and aft one. It will be noticed that half the parallelogram is sufficient, so that *Z X Y* is known as the triangle of forces.

QUESTIONS.

1. Describe the meaning of the expression co-efficient *B*, its signs and effects. (55)

2. Describe the meaning of the expression co-efficient *C*, its signs and effects. (57)

3. Would you expect the greatest disturbance of the needle from effects of sub-permanent magnetism alone to take place when the ship's head is in the same direction as when building or when her head is at right angles to that direction, and in what direction of the ship's head would you expect to find the least disturbance? (58)

4. Describe how the deviation due to the sub-permanent magnetism is compensated. (60)

5. What is meant by "the composition of forces" and "the parallelogram of forces?" Describe how they are introduced into the compensation of the compass? (61)

6. Name the co-efficients of semi-circular deviation, with their signs, which would appear on the compasses of ships built heading N.E., S.E., S.W., and N.W. (58)

7. Why are compass needles made as short as possible (55)

8. What effect has the ship's sub-permanent magnetism on the directive force of the compass needle ? (58)

9. The ship's magnetic lines of force pass obliquely upwards through a compass from starboard bow to port quarter, name the components into which this single force is resolved. (61)

CHAPTER V.

62. The Change of Polarity in Vertical Iron.—A semi-circular deviation which changes in amount as the ship changes her latitude is caused by induced magnetism in vertical iron.

Refer to fig. 24. Imagine ship A to sail from the north pole to the south pole, and that the funnel represents a mass of vertical iron. At the pole the earth's lines of force pass lengthwise through the vertical iron, and for the time being it is a strong magnet, having blue polarity in its upper half. On approaching the equator the lines of force pass more and more obliquely through the bar, and as the angle of obliquity increases it suffers a corresponding loss of magnetic effect until the equator is reached, ship C, when the lines of force pass at right angles through the vertical iron thus rendering it neutral. After crossing the equator the polarity is changed, red now appearing in the upper half, and the magnetic effect of the vertical iron continues to increase as the ship penetrates into the south hemisphere until the south pole is reached, when it again attains its maximum magnetic power.

63. Iron Vertical to the Ship's Deck such as masts, derrick posts, ventilators, davits, pillars, etc., is divided into two groups, that which deflects the needle to port or starboard, and that which deflects it to the bow or stern. The former produces co-efficient C, the latter co-efficient B.

But the uprights on one side of a ship are usually balanced by similar uprights on the other, with the result that on compasses placed in the midship line an attraction, say, to port is automatically counteracted by an equal attraction to starboard, consequently this disturbance need not enter into practical compass adjustment.

Vertical iron in the fore and aft line is not so evenly distributed relatively to the compass so that the needle may be attracted towards the bow or stern, usually towards the latter, thereby producing an additional co-efficient B, called " induced B," sometimes β (Beta) to distinguish is from sub-permanent B.

It might be profitable to discuss in greater detail the effect of vertical iron generally. It has to be kept clearly in mind that all isolated bars are assumed to be "soft" iron and that the poles in a bar depend on its position relatively to the line of dip, a red pole appearing in the end directed towards the earth's blue pole, it follows, therefore, that the upper end of a vertical bar acquires blue polarity in the north hemisphere and the lower end red, because the earth's blue pole is conceived to be somewhere below the earth's surface. Referring to fig. 39 we see four vertical rods with their top ends about level with the compass, rod No. 1 attracts the needle

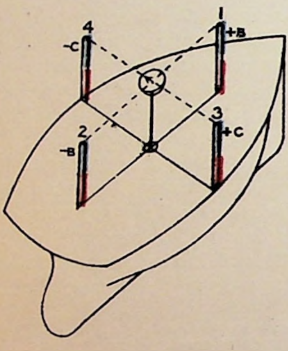


FIG. 39.

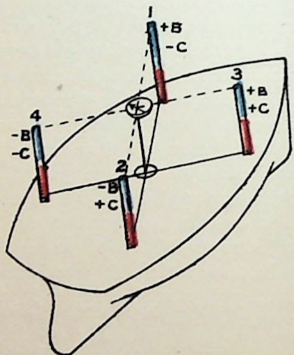


FIG. 40.

to the bow $(+B)$, and No. 2 attracts it to the stern $(-B)$. The magnetic effect of iron depends on its mass and its distance from the needle, so assuming the force of the two rods to be equal and opposite, they would counteract each other. But vertical iron abaft the compass usually predominates on board ship, so that a compensating bar is placed on the fore side of the binnacle in such a position as to compensate for the effect of the iron abaft.

The same reasoning applies to bars 3 and 4, but in this case the attraction is in the athwartship line, No. 3 attracting to starboard $(+C)$, and No. 4 to port $(-C)$, and, if these two bars were of equal magnetic intensity and equi-distant from the compass, the one would just exactly counteract the effect of the other and no deviation

would appear. A ship's compass, for this reason, is placed in the fore and aft mid-ship line.

Similarly, if we placed bars in positions, relatively to the compass, as shown in fig. 40, the several forces would balance each other and no deviation would appear. No. 1, for instance, attracts to the port bow ($+B$ and $-C$), while No. 2 attracts to the starboard quarter ($-B$ and $+C$), and, provided these two forces are equal, they will counteract each other. Likewise, the attraction of No. 3 to the starboard bow ($+B$ and $+C$) is counteracted by the attraction of No. 4 to the port quarter ($-B$ and $-C$). It will be noted that Nos. 1 and 3 combined produce $+B$ only, as the $+C$ cancels the $-C$, and that Nos. 2 and 3 combined produce a $+C$ only, as the $-B$ cancels the $+B$; and so the algebraic sum gives the resultant effect of any combination selected.

If the compass were placed on the same horizontal plane as the lower ends of these vertical rods, the signs of the co-efficient would be changed, as the effective poles would be red instead of blue. If the compass were placed on a horizontal plane midway between the ends of the rods it would be in a neutral position, as far as any one of the rods was concerned, as it would then be equi-distant from the ends of that rod and its red and blue poles would neutralise each other.

That figs. 39 and 40 are no gross exaggeration of actual conditions is evidenced by Plate II., which shows the distribution of iron

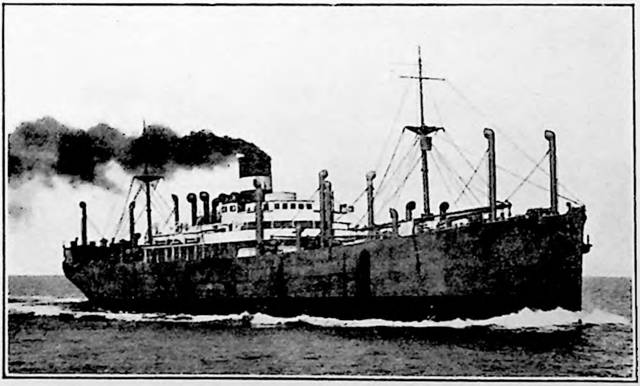


PLATE II.

derrick posts, ventilators and funnel, all in close proximity to the ship's compass which is on the upper bridge.

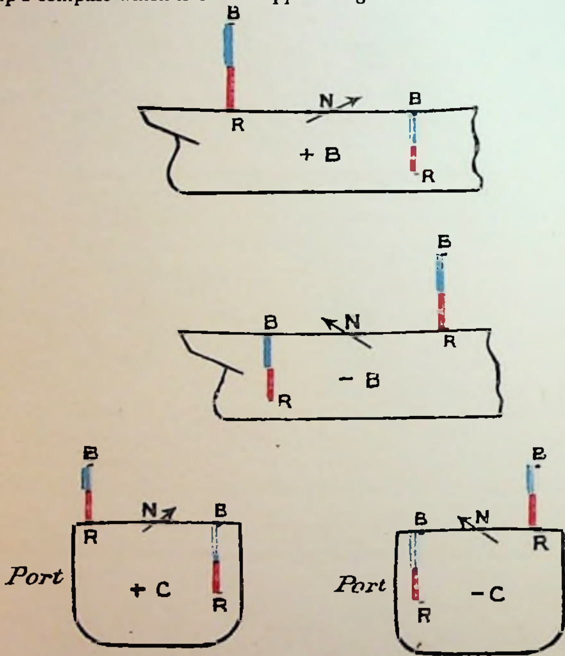


FIG. 41.

CO-EFFICIENTS *B* AND *C* FROM VERTICAL IRON. THE SIGNS REFER TO THE N. HEMISPHERE. THEY WOULD BE REVERSED IN THE S. HEMISPHERE.

Various combinations showing the action of vertical soft iron in producing semi-circular deviation on the compass is given in fig. 41. Fortunately, in merchant ships, this condition is reduced to a simple case of a preponderance of vertical iron abaft the compass.

64. The Flinders Bar.—In fig. 42, *B* represents the blue pole in the upper end of a vertical bar situated abaft the compass, the needle being drawn towards the stern, giving E. dev. when ship's head is west (No. 1), and W. dev. when her head is east (No. 3),

but no dev. when heading north or south (No. 2); because the pole in the vertical iron is then acting in a line with the compass needle. This deviation is corrected by placing a soft iron bar (Flinders bar) in a vertical position on the fore side of the binnacle

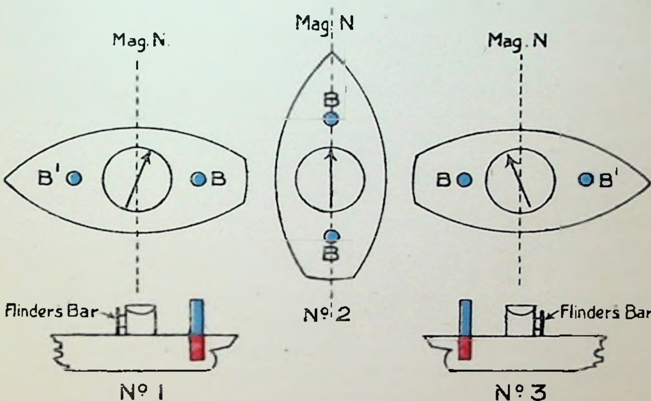


FIG. 42.

(B^1 in fig. 42) then raising or lowering it until the compass north points north magnetic. This deviation being due to soft vertical iron and the corrector being also soft vertical iron, it follows that any change in the disturbing force is met by a corresponding change in the corrector, and so the ratio between the disturbing and correcting forces remains the same, hence there should be no change of deviation from this source when the ship changes her latitude.

65. Compensate Soft Iron with Soft Iron.—If this part of coefficient B were corrected by means of a fore and aft magnet, as in figs. 25 and 26, the compensation would only hold good for the latitude in which it was made, because the magnet corrects for the same amount of deviation in all latitudes while the deviation due to the induced magnetism in vertical iron would change with change of latitude.

66. Separating the Two Parts of B.—The total B which appears on the compass when the ship's head is east or west is made up of sub-permanent B and induced B, and these two deviations are

not readily separated from each other. In practice, a blind shot is made by correcting 4 or 5 degrees with the Flinders bar, and the remaining deviation with a fore and aft magnet, and this serves well enough so long as there is no great change of latitude.

67. A Practical Method.—On the equator, however, no deviation is caused by vertical iron, the whole of *B* is then due to sub-permanent magnetism and should be corrected with the fore and aft magnet. When the ship reaches a higher latitude, and a deviation is found when her head is steadied on east or west, it will be due probably to the vertical iron now taking effect, and this new deviation, induced *B*, should be corrected with the Flinders bar.

68. Application of Theory to Practice.—The following theoretical rule, based on the assumption that the semi-circular deviation forms a symmetrical curve, gives an approximate value of sub-permanent *B*.

Enter the traverse tables with the direction of the ship's head in building yard as a course, and the value of co-efficient *C*, found when the ship's head is steadied on north or south magnetic, in a departure column, and in the corresponding difference of latitude column will be found the value of sub-permanent *B*.

EXAMPLE:—Refer to triangle *X Y Z* in fig. 34.

Ship's head in building yard	N.W. as a course, angle *Z* in fig.
Co-efficient *C* - -	say 10° in a dep. col., side *X Y*.
Gives a sub-permanent *B* of	10° in the d. lat. col., side *Z X*.

If the total *B* appearing on compass is, say, 15°, and sub-per. *B* as above is 10°, then induced *B* will be 5°. Correct 10° dev. with a fore and aft magnet, and 5° dev. with a Flinders bar when the ship is heading east magnetic.

69. A Quadrantal Deviation is produced by transient induced magnetism in horizontal beams. It is named quadrantal because it changes its name four times in a complete swing, being E. and W. in alternate quadrants as the ship's head swings round.

It is represented by the symbols *D* and *E*.

70. Co-efficient D represents the deviation caused by beams running fore and aft or athwartships and attains a maximum value when the ship's head is on N.E., S.E., S.W. and N.W., decreasing to zero on N., S., E., and W. (*See* figs. 43-44.)

$+D$ is due to continuous athwartship and divided fore and aft beams.

$-D$ to divided athwartship and continuous fore and aft beams.

$+D$ gives *E. dev.* when the ship's head is in the N.E. and.S.W. quadrants and *W. dev.* when her head is in the S.E. and N.W. quadrants.

$-D$ gives a deviation of opposite name.

Co-eff. $+D$. 

Co-eff. $-D$. 

71. Co-efficient E represents the deviation caused by diagonal beams which cross the deck at an angle of 45°. It attains a maximum value when the ship's head is on N., E., S., and W., decreasing to zero on N.E., S.E., S.W., and N.W.

$+E$ is due to beams extending continuously from the port bow to the starboard quarter, and

$-E$ when they extend from the starboard bow to the port quarter.

$+E$ gives *E. dev.* when the ship's head is in the N. and S. quadrants, and *W. dev.* when her head is in the E. and W. quadrants.

$-E$ gives a deviation of opposite name.

Co-eff. $+E$. 

Co-eff. $-E$. 

72. A Negligible Quantity.—There are comparatively few diagonal beams in a merchant ship, and the compass is usually placed at such a distance from the few there are that they have little apparent effect on the needle. Co-efficient E, when it does exist, is therefore small and is left uncompensated.

If a decided E appeared on the compass the devlation arising therefrom could be corrected by placing the soft iron spheres (fig. 44, ship No. 4) at an angle of 45° with the fore and aft line.

73. $+$D Predominates.—The co-efficient D which appears on the compass is invariably a $+D$, being the deviation caused by a preponderance of continuous athwartship beams. If the compass were placed between the ends of a cut transverse beam, such as those in the engine and boiler space of a steamer or in a sky-light or hatchway, a $-D$ would be produced. This is a very unlikely place to find

a standard compass, but it might happen in the case of an auxiliary compass.

74. How +D is Caused and Corrected.—In figs. 43 and 44 we see a couple of continuous transverse beams adjacent to the compass producing a $+D$. When the ship's head is N., S., E., or W. (fig. 43) no deviation is caused by the beam, owing to the induced poles

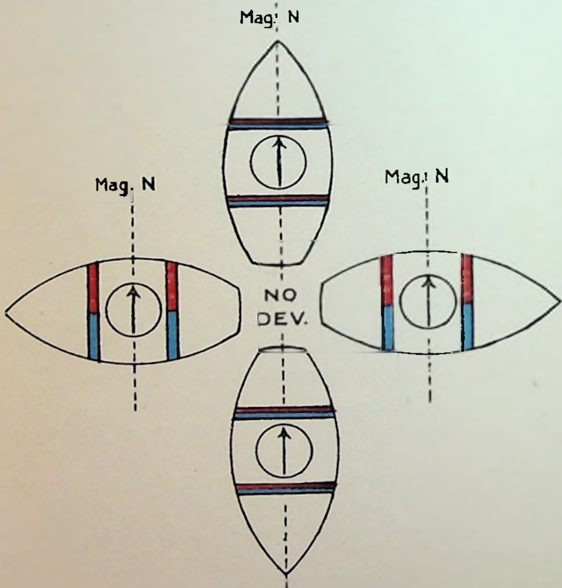


FIG. 43.

received from the earth's magnetic force acting in a direction parallel to the compass needle. But when her head is N.E. (fig. 44) No. 1) the port end of the beam is directed to the N.W. and receives red polarity, which repels the compass north to the right of magnetic north, thus giving an E. dev.

When her head is S.E. the port end of the beam is directed to the N.E. and still receives red polarity, but it now repels the needle to the left of the magnetic north, giving a W. dev.

When her head is S.W. and N.W. the starboard end of the beam is pointing northward, acquiring red polarity, but in the former case an E. dev. is produced, and in the latter a W. dev.

Thus the deviation is E. and W. in alternate quadrants, as indicated by the swing circle in the centre of the diagram.

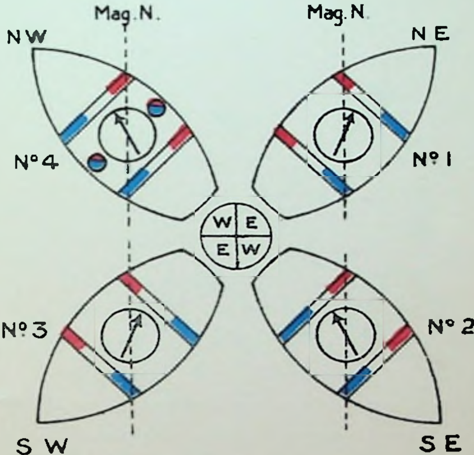


FIG. 44.

To correct co-efficient $+D$, steady the ship's head on a quadrantal point, say N.W. as in fig. 44, ship No. 4, and place soft iron correctors in the athwartship vertical plane, passing through the compass then move them close enough until the compass north points to north magnetic. (*See* the quadrantal correctors shown on the binnacle in fig. 2.) These correctors really form a divided transverse beam producing a $-D$, thus counteracting the original $+D$.

Co-efficient $-D$ may be demonstrated by means of a continuous fore and aft beam as in fig. 45 from which it will be seen that the deviation is W., E., W., E., alternately as the ship's head swings through the successive quadrants. This deviation may be compensated by placing the quadrantal spheres in the fore and aft vertical plane through the compass, ship No. 4, one before and one abaft, equidistant from, and in the same horizontal plane as, the needles, the

action of the spheres on the compass, in this case, being the same as a divided fore and aft beam which produces a $+D$, and so counteracts the effect of the existing $-D$.

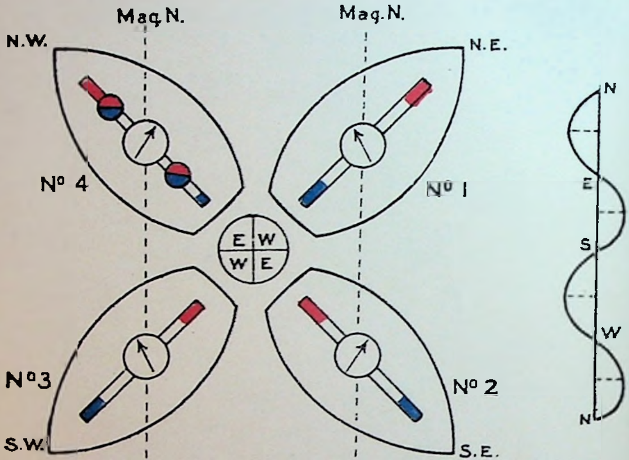


FIG. 45.—CO-EFF. $-D$ DUE TO A CONTINUOUS FORE AND AFT BEAM.

A $-D$ may also appear on a compass placed between the ends of a divided transverse beam as in fig. 46, which represents a ship heading N.E., with a W. dev. on the compass, caused by the near

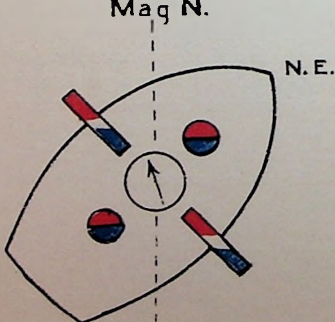


FIG. 46.—CO-EFF. $-D$ DUE TO A DIVIDED TRANSVERSE BEAM.

ends of the beams deflecting the needle to the left; this deviation may be compensated by turning the spheres into the fore and aft line.

The arrangement of horizontal iron necessary to produce coefficient E is shown in figs. 47 and 48, from which it will be seen that the maximum effect of the diagonal beam is greatest when heading on north, south, east and west, decreasing as the ship's head swings

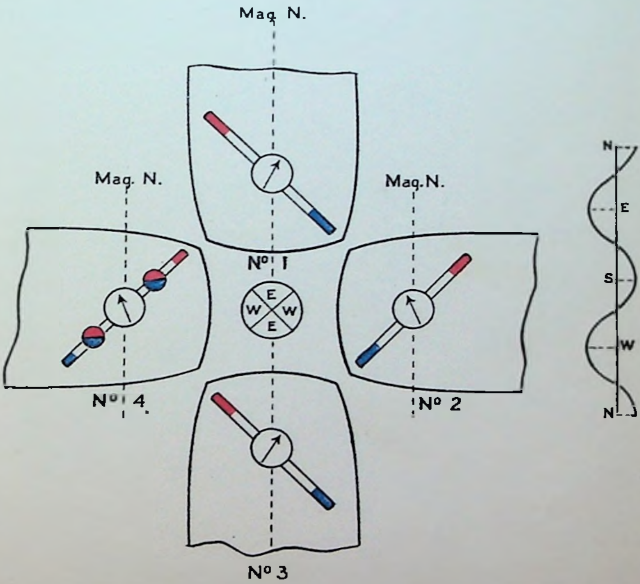


FIG. 47.—CO-EFF. + E DUE TO CONTINUOUS DIAGONAL BEAMS FROM PORT BOW TO STARBOARD QUARTER.

towards the intercardinal points where it is zero, because when heading in these directions the beams are either in alignment with the axis of the compass needle, or in their neutral position.

A $+E$ is caused when the bar is continuous from the port bow to the starboard quarter, fig. 47, and a $-E$ when it lies from the starboard bow to the port quarter, fig. 48. This deviation may be compensated by sluing the quadrantal spheres until they are parallel to the direction of the diagonal beam as in ship No. 4. The action of the spheres when in this position produce on the compass a deviation, similar in character but opposite in name, to the continuous beam.

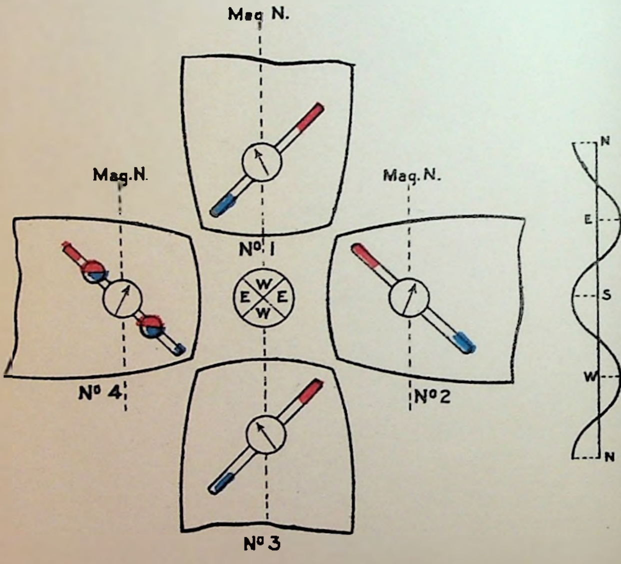


FIG. 48.—CO-EFF. $-E$ DUE TO CONTINUOUS DIAGONAL BEAMS FROM STARBOARD BOW TO PORT QUARTER.

Diagonal beams, however, are usually built symmetrically in a ship, and, in a well placed compass, the $+E$ of one automatically counteracts the $-E$ of the other for all directions of the ship's head as in fig. 49.

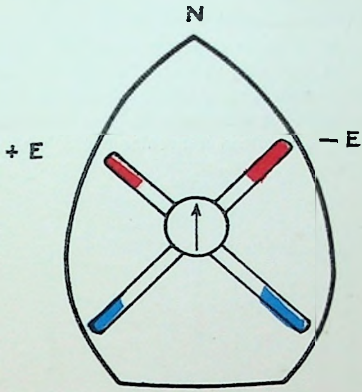


FIG. 49.

The several positions of soft iron bars and their action in producing quadrantal deviation are shown in fig. 50.

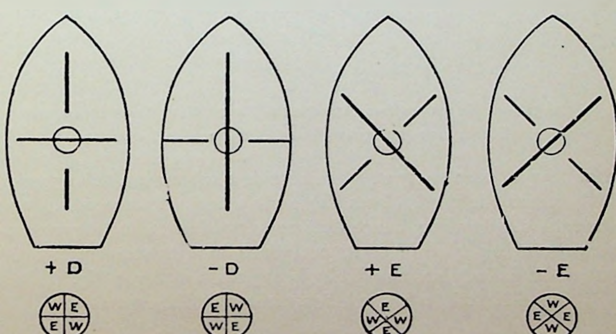


FIG. 50.

If short rods of equal magnetic intensity are arranged symmetrically round the compass as shown in fig. 51 the whole combination will cause no deviation, but the directive force of the needle will be sensibly increased on all courses by the magnetism induced in

the rods, owing to the blue poles being immediately to the north of the needle and the red poles to the south, and thus combine with the earth's force in directing the needle. If, however, a compass is placed inside a soft iron ring its directive property will be almost lost owing to the lines of magnetic force flowing round the ring thus placing the needle within a circular field. This is practically

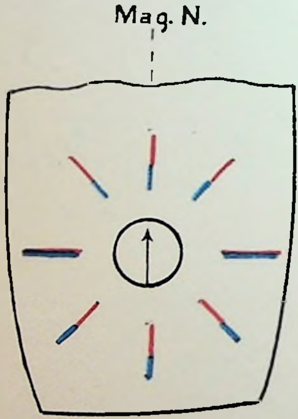


FIG. 51.—A SYMMETRICAL ARRANGEMENT OF SOFT IRON RODS, NO DEVIATION, BUT DIRECTIVE FORCE OF COMPASS INCREASED.

what happens at a compass placed inside a submarine, the spherical shell screens the needle from the earth's lines of force which pass along the shell plating, hence the necessity of installing a gyroscope compass in this type of craft, or indeed in any vessel where the compass is entirely surrounded by heavy masses of iron (fig. 16).

The quadrantal deviation is represented by the expression.

$$D \text{ sin. } 2 \text{ co.} + E \text{ cos. } 2 \text{ co.}$$

Where D represents the maximum value of co-efficient D and E represents the maximum value of co-efficient E, and co., the direction of the ship's head.

EXAMPLE :—Given co-eff. $D=4°$, co-eff. $E=2°$, find the resulting deviation on N 20° E.

$$\begin{aligned} \text{Dev.} &= D \sin. 2 \text{ co.} + E \cos. 2 \text{ co.} \\ ,, &= 4 \sin. 40^\circ + 2 \cos. 40^\circ \\ ,, &= 4 \times .64 + 2 \times .77 \\ ,, &= 2.56 + 1.54 \\ ,, &= 4.1^\circ \text{ on N. } 20^\circ \text{ E.} \end{aligned}$$

75. Like cures Like.—The quadrantal deviation is due to soft horizontal iron and the correction is made by means of soft horizontal iron, it follows, therefore, that when the compensation is properly made it should remain so for all latitudes, because the ratio between the disturbing and the correcting forces remains the same, provided the spheres are not close enough to the compass to become magnet ised by induction from the needles.

The correctors are spherical, this being the most suitable shape, and are hollow, because magnetism is chiefly confined to the surface layers of the iron and it would add nothing to their value as correctors if the spheres were solid. Occasionally an attempt is made to reduce a small co-eff. *E*, by moving the spheres a little out of the athwartship line, thus utilising them to compensate both *D* and *E*.

76. The Effect of Change of Latitude.—When studying the changes that may occur in the deviation owing to the ship changing her latitude, it is necessary to consider the relationship which exists between the disturbing force, the corrector and the needle. Should the magnetic effect of these three factors depend on the same force, they will be found to vary in exactly the same proportion, the same relative condition will continue to prevail, and no change in the deviation need be expected.

This is the case with co-efficient *D*. The soft iron causing the quadrantal deviation (the beams) and the soft iron correcting it (the spheres) also the directive force of the needle, all depend for their magnetic effect on the horizontal component of the earth's force. The power of each increases on approaching the equator and decreases when receding from it in exactly the same ratio ; they each vary directly as the earth's horizontal force, with the result that if the deviation be corrected it remains corrected in all latitudes, and if left uncompensated it will suffer no change, as the ratio between the disturbing force and the needle remains the same in all latitudes and in both hemispheres.

77. Position of Magnets and Correctors.—Certain rules have to be observed when placing correctors in position.

The compensating magnets may be placed on the deck, or anywhere in or about the binnacle, provided the centre of the fore and aft magnet lies in the athwartship vertical plane, and the centre of the athwartship magnet in the fore and aft vertical plane passing through the centre of the compass, also the vertical magnet to correct the heeling error must be exactly in the intersection of these two planes. Nor should the middle of the magnets be closer to the centre of the card than twice their own length. If placed closer the directive force of the needle would not be equalised on all points, as the action of the magnets would not be the same on both poles of the compass owing to the length of the needles. (*See* par. 4.)

The centre of the spheres and the compass needles should be in the same horizontal plane, and the spheres should be equi-distant fron the centre of the card.

The upper pole of the Flinders bar should be level with the card.

These soft iron correctors should not be closer to the centre of the card than one and a quarter times the length of the needle. If placed closer they are liable to become magnetised by induction from the needles and rendered useless as correctors.

78. Co-efficient A.—We have discussed co-efficients *B*, *C*, *D*, and *E*, but there remains another one, co-efficient *A*, which represents a deviation of the same name and amount on all courses. It is really an index error, due usually to a mechanical defect in the compass, such as the magnetic axis of the needles not being parallel to a line drawn through the north and south points of the card, or the card itself not being accurately centred and graduated, the lubber line misplaced, or an error in computing the magnetic bearing of the distant object by which the compass was adjusted. The centreing of the card may be roughly tested by deflecting it a few degrees and letting it swing, when, if properly poised, it should always indicate the same direction on coming to rest. The lubber line may be tested by bringing the sight vanes in a line with the stem, the centre of the masts, or any upright which is in the fore and aft midship line of the ship, and then observing if the lubber line lies exactly under the thread of the vanes.

An apparent *A* may be due to frictional resistance between the cap and the pivot, which will draw the card round in the same direction

as the ship's head when she is swung hurriedly for deviation. West dev. appears when her head is turning to port, and E. dev. when turning to starboard. This, however, may be prevented by keeping the ship's head long enough in one direction to allow the card time to settle, or by swinging the ship's head to the right and to the left, and taking the mean of the resulting deviations.

The value of A is the mean of the deviation on the cardinal and inter-cardinal points, and takes the name of the greater, $+A$ when east, $-A$ when west. In good compasses it is small in amount and causes no practical inconvenience.

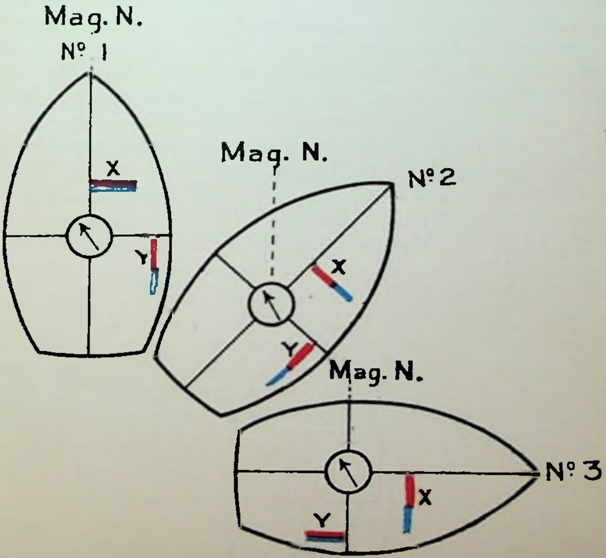


FIG. 52.—CO-EFFICIENT - A.

A real A due to magnetic attraction may be demonstrated on the deviascope by a peculiar arrangement of soft iron as shown in fig. 52. X and Y being two bars placed at such a distance from the compass that the deviation due to one is equal to that of the other, and it will be found on swinging ship that the combined action of both causes

an unvarying deflection of the needle for all directions of ship's head. Suppose each bar of soft iron to be capable of producing 3° deviation when in its position of maximum efficiency, which will be with its length in the plane of the magnetic meridian. Now when the ship is heading north, No. 1, we find *X* lying at right angles to the meridian, and so, for the time being it is neutral and causes no deviation. But the north end of *Y* is red and repels the needle to the left with a force which is capable of producing, say, 3° W. deviation ($-A$). Now, as the ship's head swings away from north the deviation due to *Y* decreases, owing to the bar taking up a position more and more inclined away from the meridian. But meanwhile *X* has developed a red pole in its north end, which repels the needle to the left and, as the increase of deviation due to *X* is equal to the decrease of deviation due to *Y*, we find when heading N.E. No. 2, that the deviation is still 3° made up of 1½° from each bar. Eventually when heading east (No. 3), the whole of the 3° deviation is due entirely to *X*, which is now lying in the plane of the meridian, *Y* being at right angles to it and is consequently out of action. Thus the combined effect of *X* and *Y* is to produce a deviation constant in name and amount on all points.

A$+A$ could be shown by shifting *Y* over to the port side of the compass and *X* to the port side of the fore and aft line as in fig. 53.

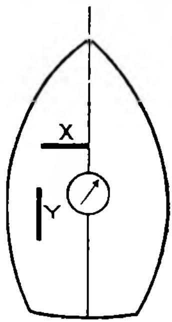


FIG. 53.—CO-EFFICIENT + A

The deviation due to this soft iron should remain the same in all latitudes owing to the directive force of the needle increasing and decreasing in the same proportion as the magnetic intensity of the

bars, the value of both depending on the earth's horizontal force. Although co-efficient A due to index error may be obviated by shifting the lubber line to the right, or left, by a number of degrees equal to the index error, this will only effect a cure for steering courses only, and it will still have to be applied when taking bearings by the compass. Another arrangement of the bars to produce a constant deviation is in the form of a T, fig. 54, with the compasses

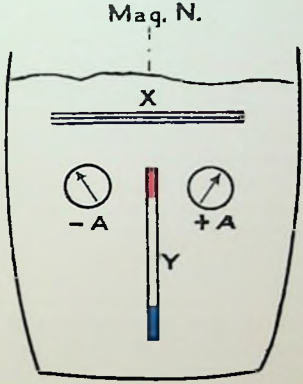


FIG. 54.

placed in the corners out of the midship line. When the ship's head swings round, bar X acquires induced magnetism as fast as bar Y parts with it, the resultant effect of the two forces being always the same, $+A$ appearing on the starboard compass and $-A$ on the port one.

79. Gaussin Error.—When a ship has been kept heading in the same direction for a considerable time, either in port or at sea, she receives from the earth a dose of induced magnetism. Now, iron of such a quality as the theoretically soft variety, described in par. 47, rarely exists on board ship, so that some of the induced magnetism is retained temporarily. The effect is not apparent when the ship's head is kept in the same or in the opposite direction, but a deviation appears as soon as her head is altered, which reaches a maximum when the course is at right angles to the original direction.

Consider what happens in the case of a vessel bound up the

English Channel. She is heading east, the athwartship beams are pointing towards the north, the port ends of which acquire red polarity and the starboard ends blue but no deviation appears, because the beams are parallel to the direction of the needle.

The course is altered from east to about north, in order to pass through the Straits of Dover, with the result that the compass north is drawn to the starboard side of the ship by the retained blue pole on that side, the beams being now at right angles to the needle. An east deviation is thus produced which, if not allowed for, will throw the ship to the eastward of her expected position. The amount of this temporary deviation is uncertain, as it depends on the magnetic permeability of the iron, but it gradually decreases, although some time may elapse before it entirely disappears, perhaps a few hours, or even a day or two. It is therefore a wise precaution to swing the ship's head on the new courses that are to be steered during the night and to find the actual deviation thereon before darkness sets in.

The deviation due to this unstable magnetism is known as the "Gaussin" error.

80. Recapitulation.—We have endeavoured to describe the system whereby the total deviation of the compass is resolved into five distinct components, and also the tentative method of compensating the three most important of them, namely, *B*, *C*, and *D*.

I.—A semi-circular deviation arising from sub-permanent magnetism, which was resolved into a fore and aft component—co-eff. *B*—corrected by means of a fore and aft magnet when the ship's head is on E. or W. magnetic; and an athwartship component—co-eff. *C*—compensated with an athwartship magnet when the ship's head is on N. or S. magnetic.

II.—A semi-circular deviation caused by transient induced magnetism in vertical iron situated in the fore and aft line of the ship—co-eff. induced *B*—compensated with a Flinders bar when the ship's head is on E. or W. magnetic.

III.—A quadrantal deviation caused by transient induced magnetism in horizontal iron, usually continuous athwartship beams—co-eff. $+D$—compensated by means of soft iron spheres one on each side of the compass, when the ship's head is on one of the inter-cardinal points.

QUESTIONS.

1. Which is the red and which is the blue pole of a mass of soft vertical iron by induction, and what effect would the upper and lower ends of it have on the compass needle (*a*) in the northern hemisphere, (*b*) in the southern hemisphere, (*c*) on the magnetic equator ? (62)

2. Does the magnetism induced in vertical iron usually have any effect in producing the co-efficient *C*, ship upright, or is it generally produced by sub-permanent magnetism alone ? State your reasons for saying so. (63)

3. Can semi-circular deviations be produced by any other force than the sub-permanent magnetism of the ship ? (64)

4. If induced *B* and sub-permanent *B* are corrected by a magnet alone, as is sometimes the case, what is frequently the consequence on the ship changing her magnetic latitude and hemisphere ? (65)

5. How should each of these two parts of *B* then, strictly speaking, be compensated? And describe how you would proceed in order to improve, if not to perfect, the compensation of co-efficient *B*, on reaching the magnetic equator. (65) (66) (67)

6. Describe quadrantal deviation. Why is it so called, and what co-efficients represent it ? (69)

7. Describe co-efficient *D*, its signs and effects. (70)

8. Describe co-efficient *E*, its signs and effects. (71)

9. How is co-efficient *D* compensated, and if it be properly adjusted is it likely to remain so in all latitudes and both hemispheres ? State your reasons (74) (75) (76)

10. Why is co-efficient *E* seldom compensated, and describe how you would correct this co-efficient ? (72)

11. State the rules and conditions to be observed when placing in position the magnets and soft iron correctors used in compensating the compass. (77)

12. Describe the meaning of the expression co-efficient *A*. (78)

13. What is " Gaussin " error ? How and when is it acquired, and what effect has it on the compass ? (79)

14. Describe briefly the tentative method of compass adjustment as generally practised by adjusters in ships of the Mercantile Marine. (80)

15. Where should bars of vertical soft iron be placed relatively to the compass to produce $+B, -B, +C$ and $-C$? (63)

16. Illustrate by sketches the position of soft iron bars to produce co-efficients *D* and *E*. (74)

17. What is the effect on the needle of horizontal soft iron rods when arranged symmetrically round the compass ? (74)

18. A magnetic compass fails to function inside a submarine, what is probably the cause of this ? (74)

19. Show by a sketch how a co-efficient *A* may be demonstrated at a compass by soft iron bars. (78)

CHAPTER VI.

81. Heeling Error: Its Cause and Effect.—When the ship takes a list a deviation appears, called heeling error, which is greatest when her head is N. or S. by compass, as the forces causing the error are then at right angles to the needle, decreasing to zero on E. and W. courses, thus heeling error simulates co-efficient *C*.

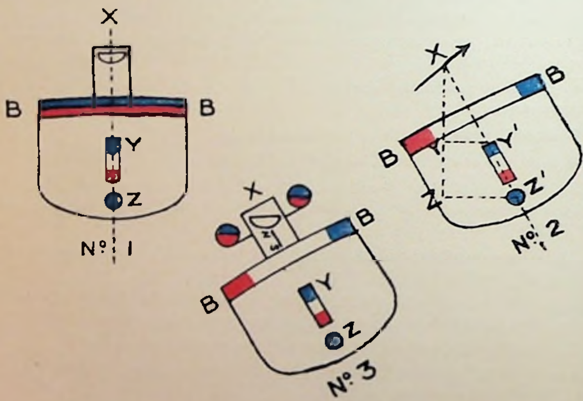


FIG. 55.

It is due to the ship's force, when she heels, acting obliquely to the vertical plane passing through the compass. A general notion of the cause of heeling error may be acquired by drawing the transverse section of a ship as in fig. 55, and conceiving the hull to swing, like a pendulum, from side to side, the compass needle being the axis. It will be obvious that the magnetic forces which lay in the vertical plane passing through the compass when the vessel was upright swing to one side of that plane when she heels.

If the force below the compass be represented by a blue pole, the needle will be attracted downwards; then, when the ship heels over, the blue pole will move to the high side of the vertical plane, and the downward attraction will partake of a horizontal component which draws the needle to the high side. Conversely, if the controlling pole below the compass be red the needle will be deflected upwards, and when the ship heels the north point will be repelled tc the low side.

The total force of the ship which produces heeling error is resolved into the same three components as when upright, namely—the sub-permanent magnetism, induced magnetism in vertical iron, and induced magnetism in horizontal iron. Each part may be considered separately, but the error appearing on the compass is, of course, due to the combined effect of them all.

82. Attraction to High Side.—Fig. 55 represents a vessel heading N. in the north hemisphere, and shows the distribution of the three principal forces which draw the north point of the compass to windward, these are :—

(1) The sub-permanent blue pole predominating on the compass due chiefly to the ship's head having been northerly in the building yard.
(2) Vertical iron situated wholly below the compass.
(3) Continuous athwartship beams.

For example, in fig. 55, X represents the position of the compass, Y the blue pole in the upper end of vertical iron, Z the sub-permanent blue pole of the ship, and B B a continuous athwartship beam.

When the ship is upright as in No. 1. the three forces are all operating in the vertical plane passing through the compass. The blue poles, Y and Z, are attracting the needle downwards, and if the needle were free to respond the north point would dip slightly. But when the ship heels over, as in No. 2, we find the sub-permanent blue pole has moved from Z to Z^1, and the induced blue pole in vertical iron from Y to Y^1 while the horizontal beam has tilted up, and now partakes of vertical induction, a blue pole appearing in its upper end. The three forces are now situated to windward of the vertical plane passing through the compass, and each is drawing the needle to the high side.

In the triangle of forces $X\,Z\,Z^1$, the side $Z\,X$ represents the magnitude of the downward attraction due to sub-permanent magnet-

ism and the side $Z Z^1$ represents the magnitude of the horizontal component of that force which produces the heeling error. Similarly, the side $X Y$ represents the downward attraction of the vertical iron, and the side $Y Y^1$ the magnitude of its power to cause heeling error, the direction and magnitude of the resultant in this case being represented by $X Y^1$.

83. Attraction to Low Side.—Fig. 56 illustrates the particular arrangement of the three components which will deflect the needle to leeward.

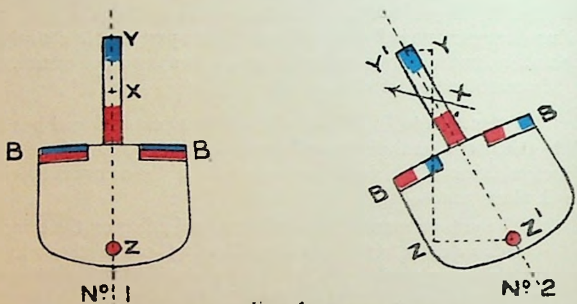


FIG. 56

(1) The sub-permanent red pole predominating, due usually to the ship's head having been southerly in the building yard.

(2) Vertical iron having its top end extending above the level of the compass.

(3) Divided athwartship beam.

For example, the red sub-permanent pole has moved from Z to Z^1, and is now on the high side of the vertical plane passing through the compass, thus repelling the needle to the low side. The induced blue pole in the upper end of the vertical iron has fallen to the low side and is drawing the north point after it, whilst the poles in the divided beam, adjacent to the compass, are also deflecting the needle to leeward.

In the triangle of forces $X Z Z^1$, the side $X Z^1$ represents the magnitude and direction of the force arising from sub-permanent magnetism, $X Z$ the vertical component which causes no deviation and $Z Z^1$ the horizontal component producing the heeling error.

Similarly in triangle $X\ Y\ Y^1$ the side $Y\ Y^1$ represents the horizontal component of the vertical iron which attracts the needle to leeward

84. Change Hemispheres, Change Poles in Vertical Iron.— Keeping in mind the fact that the poles in vertical iron change colour on crossing the equator, *see* fig. 24, it will be understood that the polarity of the soft iron in figs. 55 and 56 only applies to the north hemisphere. In the south hemisphere the poles would be reversed, so that soft iron arranged as in fig. 55 would then cause an error to low side and that of fig. 56 to the high side.

85. Some Obvious Facts.—It is obvious that if the heeling error is not allowed for when the compass north points to the high side, the ship. by following the needle, will find herself to windward of the expected position when steering on northerly courses, and to leeward when she is on southerly courses. The reverse will be the case should the needle be drawn to the low side.

When compass north is drawn to high side it will be necessary, therefore, in order to make good a given course, to keep away when sailing on northerly courses and closer to the wind when on southerly courses, but when compass north is drawn to the low side keep closer to the wind on northerly courses and away on southerly. This rule applies to both hemispheres.

86. Correction of Heeling Error.—The amount of heeling error can be found by inclining the vessel, and corrected by placing in the binnacle, exactly under the centre of the compass card, a magnet vertical to the ship, then raising or lowering it until the amount of error is removed. (*See* vertical magnet in fig. 55, No. 3.) When the correction is made for any degree of heel, the error is compensated for every angle of inclination, because the vertical magnet remains in the same position with respect to the compass and the disturbing forces.

87. A Saving of Labour.—To forcibly incline a big ship would be a serious job ; it is not done in practice. It has been pointed out that the forces productive of heeling error operate in the vertical plane passing through the compass when the ship is upright, and deflect the north point of the needle either upwards or downwards. Now, this vertical angle can be determined, and suppose, by way of illustration, it were a downward attraction, of, say, 10° due to a blue pole below the compass, then all we have to do is to introduce the red pole of a magnet below the compass so that it may produce an upward repulsion of 10°.

88. The Vertical Force Instrument.—This angle is measured by means of Lord Kelvin's Vertical Force Instrument, fig. 57. It is a modified dipping needle, designed for comparing the vertical force on board ship with the vertical force on shore.

The instrument is taken on shore to a position free from local magnetic attraction, and when placed in the magnetic meridian the north point of the needle will be found to dip downwards in the north hemisphere. The needle is brought into the horizontal plane by means of a sliding weight, thus compensating the dipping effect of the earth's normal force.

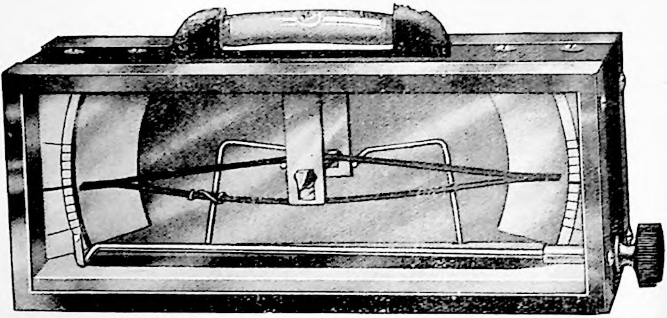


FIG. 57.—KELVIN VERTICAL FORCE INSTRUMENT.

The instrument having been horizontalised on shore is now taken on board and placed in the exact position of the compass needle. If it remains horizontal it indicates there is no vertical force in the ship to cause heeling error. But should the north end dip downwards it shows that blue polarity exists below the compass, which will draw the compass north to high side when the ship heels. A vertical magnet is then placed in the centre of the binnacle, with its red pole next the compass, and raised or lowered until the needle is again horizontal.

89. Vertical Force varies as the Tangent of the Dip.—That part of the heeling error due to vertical iron follows the law of vertical induction (*see* fig. 24) and decreases as the equator is approached, vanishes on the equator, and increases with a changed name on crossing into the opposite hemisphere.

But the compensating magnet, being a permanent one, corrects for the same amount of error always, and cannot meet the change of heeling error due to the changing effect of vertical iron. Consequently the compensation only holds good for the latitude in which it is made, and the vertical magnet will probably have to be raised or lowered as the ship sails north or south, and perhaps turned end for end when the hemisphere is changed.

Theoretically, the part of the heeling error due to soft iron should be corrected with a soft iron corrector, and the part arising from sub-permanent magnetism with a permanent magnet on the same principle as we fixed up the two parts of co-efficient B in Chapter V.; but a convenient method of applying this in practice has not yet been devised.

90. A Coincidence.—The heeling error due to the continuous athwartship beams is automatically counteracted by the quadrantal spheres used in correcting co-efficient $+D$. The correctors really form a divided beam drawing the compass north to the low side in the north hemisphere, and as they produce a deviation equal in amount, but opposite in name to that produced by the continuous beams, it is a satisfactory coincidence that they compensate for this part of the heeling error as well as the quadrantal deviation.

91. Sub-permanent Magnetism versus Transient Induced Magnetism.—The heeling error found in practice is due therefore to the sum or difference of the sub-permanent magnetism and the transient induced magnetism in vertical iron.

In fig. 55, for example, the two blue poles Z^1 and Y^1 are acting in combination, and unite in drawing the needle to the high side. At the equator the vertical iron is neutral, Y^1 vanishes, and the heeling error is then due solely to Z^1, the sub-permanent magnetism.

On crossing into the south hemisphere the upper end of the vertical iron will acquire red polarity, which will act in opposition to the sub-permanent blue pole, slightly at first, but with increasing effect as the latitude increases, until, eventually, the force of the induced red pole will equal the force of the fixed blue. They will counterbalance, and no error will appear.

On proceeding further south the effect of the vertical iron will increase and dominate the position and repel the needle to the low side. From this we infer that the rule regarding heeling error is not the same in both hemispheres. If the compass north is drawn to

high side in the north hemisphere it may be drawn to the low side in the south hemisphere, especially if a sufficiently high opposite latitude is reached to enable the effect of red transient induced magnetism in vertical iron below the compass to overcome the effect of the blue sub-permanent magnetism.

92. The Heeling Error Decreases as the Directive Force Increases.—Although the sub-permanent magnetism in the early days of a new vessel undergoes considerable reduction, it eventually settles down to a fairly steady force when the ship becomes seasoned. Nevertheless the heeling error due to this force decreases on approaching the equator and increases on going into higher latitudes, retaining the same name always. This is owing to the fact that the directive force of the compass needle is greatest at the equator, and in consequence thereof is more difficult to disturb.

Effect on change of course or tack.—When heading northerly on, say, the starboard tack and the needle is drawn to high side, an east error appears, but, when the ship is put on the port tack, still heading northerly, a west deviation is the result, so, obviously, if the ship changes tacks the heeling error changes its name. Again, if the ship is heading north, still heeling to port with the needle drawn to high side, the deviation is east, but, if she heads south, still heeling to port and needle still drawn to high side, the deviation is west, so, if the course is changed from northerly to southerly and ship still heels to the same side, the error changes its name.

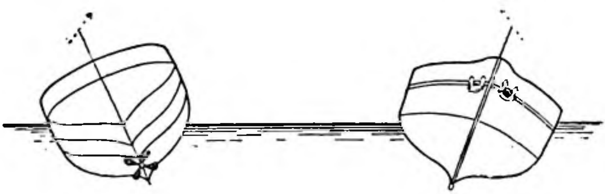


FIG. 58.

HEAD NORTH
HEELING TO PORT
ERROR EAST.

HEAD SOUTH
HEELING TO PORT
ERROR WEST.

If, however, she is on one tack when heading northerly and changes to the other tack and heads southerly, the error retains the same name. Thus, briefly, a change from northerly to southerly

courses only, or of tack only, but not of both, causes the heeling error to change its name.

Readjusting heeling error at sea.—If the heeling error were left uncorrected and there was a strong downward vertical force, the compass north would, at each roll, be alternately attracted to whichever happens momentarily to be the high side of the ship, the result being a very unsteady compass, which might oscillate two or three points on each side of the course, especially in high latitudes when the directive force of the needle is diminished. This was a frequent source of worry when rolling down the "roaring forties" before a westerly gale in the days of the Colonial clippers. This inconvenience, when it exists, might be remedied in many cases by re-adjusting the heeling error. The difficulty, however, would be to know just how much to raise, or lower, the vertical correcting magnet to compensate for the new heeling error due to the ship having changed her latitude.

That part of the heeling error due to vertical iron changes with the earth's vertical force, and as the vertical force instrument enables us to measure the vertical force of the earth at one place relatively to that at another we have here, in conjunction with the information given in the vertical force Chart No. V. Appendix, a means of finding out, experimentally, how to regulate the position of the vertical magnet in the binnacle to compensate for the change of heeling error (the actual amount of which need not be known) due to change of latitude.

Suppose, for example, at Glasgow where the earth's vertical force is represented by $+2.5$, the counterweight of the vertical force instrument is at 20 on the scale when it is horizontalised on shore, at what reading should the weight be placed at Demerara where the earth's vertical force is $+0.75$ in order to keep the needle horizontal?

This is a question of simple proportion. The scale reading (n) at a new place is to the scale reading (n^1) at a former place as the vertical force (V) at the new place is to the vertical force (V^1) at the former place.

$$\frac{n}{n^1} = \frac{V}{V^1}$$

$$\frac{n}{20} = \frac{+0.75}{+2.5} \text{ from which } n = +6.$$

The plus sign indicates that the ship is still north of the equator and that the north end of the needle still seeks to point downwards.

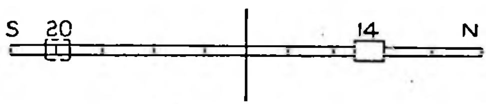
If the weight is now moved inwards from the 20th division to the 6th division of the scale marked on the south half of the needle it should just balance the dipping effect of the earth, and the needle, if under the influence of the earth's normal force only, ought to lie in a horizontal plane at Demerara.

But, suppose the same ship from Glasgow is now off the Cape of Good Hope in lat. 40° S., long. 20° E., the steering compass is very unsteady and giving trouble and it is decided to alter the heeling error magnet in the hope of steadying the compass. There is a vertical force instrument on board ; at what scale reading should the counterweight be placed before using the instrument?

On referring to Chart V. we find the earth's $V.F.$ at this position to be -1.75 (V), at Glasgow it was $+2.5$ (V^1) and the scale reading was 20 (n^1) so,

$$\frac{n}{20} = \frac{-1.75}{+2.5} \text{ from which } n = -14.$$

The minus sign indicates that the ship has crossed the equator and that the north end of the needle now desires to point upwards, instead of downwards as at Glasgow. So the weight should be moved from 20 on the south end of the needle to 14 on the north end and, if the vertical force instrument were acted on by the earth's



force alone at this place, the needle should lie horizontal. Now, lift the compass bowl out of the binnacle, suspend the vertical force instrument in the position previously occupied by the compass card, and if the needle takes up a horizontal position it indicates that the heeling error is corrected and nothing need be done, but should it not lie in the horizontal plane it shows that there is a vertical force in the ship causing an error which pulls the compass alternately to one side then to the other when the ship rolls. To correct this error move the vertical correcting magnet in the binnacle up, or down, or turn it end for end if need be, until the needle takes up a horizontal position. Put the compass bowl back into the binnacle and observe how it behaves now.

QUESTIONS.

1. Would you expect any change to be caused in the error of your compass by the ship heeling over either from the effect of the wind or cargo, etc ? (81)

2. Describe the principal causes of heeling error. (81)

3. Towards which side of the ship will the needle be drawn by a continuous transverse beam when the ship heels over in (*a*) the north hemisphere, (*b*) the south hemisphere ? (82-84)

4. What is the effect on the needle, when the ship heels over, if the compass is placed between the ends of a divided athwartship beam (*a*) in the northern hemisphere, (*b*) in the southern hemisphere ? (83-84)

5. A vertical iron bar is situated below the compass, what heeling error would it cause, if any, (*a*) in the northern hemisphere, (*b*) in the southern hemisphere ? (82, 84)

6. Under what conditions (that is, as regards position whilst building and the arrangements of iron in the ship) is the north point of the compass needle usually drawn to the high side of the ship in the northern hemisphere ? (82)

7. Under what conditions, as a rule, is the north point of the compass needle usually drawn to the low side of the ship in the northern hemisphere ? (83)

8. What effect has heeling error, if not allowed for, on the assumed position of the ship ? (85)

9. What should be done in order to make good a given compass course when steering on northerly and southerly courses when (*a*) the compass north is drawn to high side, (*b*) when drawn to low side ? (85)

10. Why is heeling error greatest when the ship's head is N. or S. by compass and least when her head is E. or W.? (81)

11. Explain how the heeling error, due to induced magnetism in iron vertical to the ship's deck, varies as the ship changes her geographical position. (89)

12. Explain how that part of the heeling error due to the permanent part of the magnetism of the ship varies as she changes her geographical position, and what is the reason of this ? (92)

13. Describe how the heeling error is corrected without actually heeling the ship. (88)

14. Can the compensation of the heeling error be depended on in every latitude ? If not, state the reason. (89)

15. What effect has the soft iron spheres used for compensating co-efficient $+D$ on the compass needle when the ship heels over, and what part of the heeling error do they correct for, if any? (90)

16. Under what circumstances does the heeling error change its name, and retains the same name ? (92)

CHAPTER VII.

93. Swinging Ship.—Preliminaries. Nautical instruments designed and manufactured by the best firms are as perfect as modern scientific knowledge and ingenious workmanship can produce, but the compass is a delicate instrument and cannot withstand the wear and tear of time and rough handling. It is desirable to guard against the more obvious defects before proceeding with the adjustment.

The degrees and points round the rim of the card should be carefully scrutinised for faulty graduations, and the cap and pivot examined with a magnifying glass; the cap should be free of cracks and the pivot point sharp.

The card should be accurately centred. This will be noticed by making a pencil mark on the inside of the bowl at the level of the card, and if not properly centred, the edge of the card will rise and fall from this mark when it is spun round gently on its axis. The point of the pivot should be at the centre of the bowl, inaccuracy in this respect being detected by unequal distance between the edge of the card and the side of the bowl.

The lubber line should be tested by bringing the sight vanes of the compass in line with the ship's stem, or the centre of the masts, and observing if the lubber line is in the same vertical plane.

The period of the card should be noted by deflecting it with a magnet about 40° away from the lubber and counting the number of seconds between the times of two successive transits of the original degree in the same direction across the lubber line. The period is usually about 33 seconds. The card when deflected should always come to rest indicating the same direction.

The prism of the azimuth mirror is tested by observing the bearing of an object with the arrow up and arrow down; the two bearings should agree, if not, make them do so by means of the retaining screws at the side of the prism.

The iron spheres should be tested for retained magnetism by turning each separately on its vertical axis, and noting if there is any change in the deviation produced. It is difficult to get rid of this superfluous magnetism in soft iron, although rolling it on the deck may eliminate some of it, but heating it to a critical temperature of 800° centigrade and cooling slowly is the surest way of bringing the soft iron back to its normal state. If the spheres are unduly magnetised they should be exchanged.

Loose iron in the vicinity of the compass should be removed and davits, ventilators and adjacent movable iron should be in its sea position.

Electric lights, also wireless transmitting installations, should be switched on and off frequently during the process of adjusting to guard against leakage of current. It might here be remarked that if a single wire is led close to the needle and parallel to its axis, the north end of the needle will be deflected to the right or left of the direction in which the current flows through the wire as the needle tends to set itself at right angles to the wire. Ampere gave the following rule to ascertain the direction taken by the north seeking pole of a magnet when under the influence of a current:

"Let the observer imagine that he is swimming in the wire in the direction of the current with his face towards the magnet, then the north seeking pole will turn in the direction of his left hand." *See* also (page 136).

The sun, when visible, is the most reliable and satisfactory body to work with when swinging ship for deviation. The true azimuths for every fourth minute covering the period to be occupied by the proposed operation are taken from Time Azimuth Tables, to which is applied the local variation—(east variation to left of true bearing, west variation to the right) in order to get the sun's magnetic bearing. The difference between the magnetic bearing and the compass bearing is the deviation for the direction of the ship's head at the time.

A complete curve, or table, of deviations for a compass may be drawn up by steaming the ship round slowly in a circle, and steadying her head on every second or fourth point, the cardinal and intercardinal points usually—for a few moments, just long enough to let the card settle and to get a good compass bearing of an object whose magnetic bearing is known, the deviation, as before, being the difference between those two bearings. The deviations having been

got in this manner for each of the eight principal points, a curve may be drawn on a Napier's diagram, page 143, which will include the deviation on all the intermediate points; or, if the deviation on the equi-distant points is written in tabular form, the deviation on the odd points may be filled in as found by interpolation.

If a shore object is used the radius of the circle described by the ship, when swinging, should be as small as possible, so that the magnetic bearing may not be altered by the changing position of the vessel; the object should, therefore, be a considerable distance off, 4 or 5 miles at least. Herein lies one of the advantages of using the sun, change of position does not alter materially his magnetic bearing and, as the ship is often under way when the compass is being adjusted, no fine manoeuvring of the ship is demanded.

It is not always easy to select a suitable shore object and to get its magnetic bearing. If the exact position of the ship can be plotted on the chart the bearing of the object from that spot can usually be got from the chart also. The best results are obtained when the ship can be brought into a position from whence two objects are seen in a line with each other, their transit bearing being taken from the chart, or an Ordnance Survey map. Adjusters on the Clyde have for many years made use of a church spire and two chimneys in Greenock, when swinging ship at the Tail of the Bank, and the transit bearings of these objects are now given on Admiralty chart 2006.

The mechanical operation of adjusting the compass by these marks might probably be carried through in the following manner, the heeling error having previously been corrected with the aid of a vertical force instrument, and a suitable length of Flinders bar placed in position to compensate for an estimated induced B.

No. 1. Refer to fig. 59, head east magnetic, compass bearing, say, S. 33° W., magnetic bearing S. 26° W., deviation 7° W. (west because the magnetic bearing lies to the left of the compass bearing). Insert fore and aft magnet, or magnets, until the transit bearing by compass is also S. 26° W. This compensates the semi-circular deviation due to the fore and aft force in the ship.

No. 2. Head north magnetic, compass bearing, say, S. 16° W., magnetic bearing S. 26° W., deviation 10° E. (east because the magnetic bearing lies to the right of the compass bearing). Insert an athwartship magnet, or magnets, until the transit bearing by compass

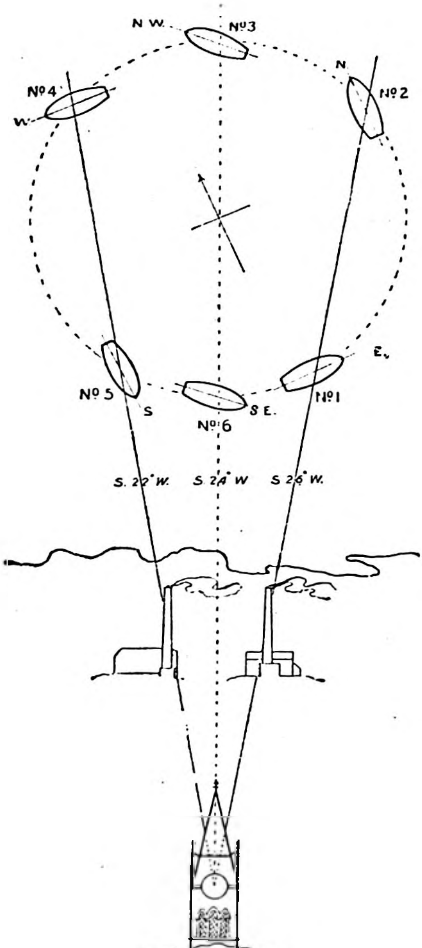


Fig. 59.—Swinging Ship for Deviation.

is also S. 26° W. This compensates the semi-circular deviation due to the athwartship force in the ship.

No. 3. Head N.W., compass bearing say S. 27° W., magnetic bearing S. 24° W., deviation 3° W. Put the quadrantal spheres on the brackets and move them in to the compass until the transit bearing by compass is also S. 24° W. This compensates the quadrantal deviation due to induced magnetism in the transverse beams.

NOTE.—The angle between the transit bearings being small, only 4°, the angle can readily be divided up by eye, and the intermediate bearings of S. 25° W., S. 24° W., and S. 23° W. estimated with considerable accuracy. The angle between the bearings in the figure is grossly exaggerated in order to get room to show the ship being swung round.

No. 4. Head west magnetic, the transit bearing by compass should be S. 22° W. as we just cleared off the deviation due to the ship's fore and aft force when her head was east. Suppose, however, the bearing to be S. 24° W. by the compass leaving 2° W. deviation. Now move the fore and aft magnets away from the compass and remove 1° of this residual deviation.

No. 5. Head south magnetic. The transit bearing by compass should be S. 22° W., as we just cleared off the deviation due to the athwartship force when the ship's head was north. If the compass bearing is not S. 22° W. the athwartship magnets are moved a little to correct for half the remaining deviation.

No. 6. Head S.E. magnetic. The compass bearing of the transit should be S. 24° W., as we just cleared off the quadrantal deviation when the ship's head was N.W.; but should a small deviation appear then move the spheres nearer to, or away from, the compass and clear off half the remaining deviation.

It is rarely possible to eliminate the deviation on all headings so, when on the second swing round, the residual deviations are observed, recorded in a table and applied by the navigator as required; the whole operation occupying about two hours. The method of steadying the ship's head in the desired magnetic directions by means of the pelorus is described on page 10.

Liverpool is fortunate in having numbers painted at suitable places on the face of dock walls; each number when seen in a line with a very prominent church spire gives the true bearing of the transit, which is easily converted into its corresponding magnetic bearing by applying the variation for the year. The River Mersey

in the vicinity of the Landing Stage flows nearly north and south, so when a ship is at anchor, the deviations may be checked, or the compass corrected, when she swings to the turn of the tide (fig. 60).

Notice to Mariners.—For the purpose of adjusting compasses, the numbers and shapes along the river walls, etc., between the Waterloo Dock and the Canada Basin, denote the true bearings of the Spire of "St. Martin's in the Fields" Church (Vauxhall Road).

The numbers indicate every 5 degrees and the true bearing of this Spire in line with the Victoria Tower is 92° 26′ 17″, but for the purpose of clearness that Tower has been marked $92\frac{1}{2}$°.

The old numbers and shapes which gave the true bearings of Vauxhall Chimney have been abolished.

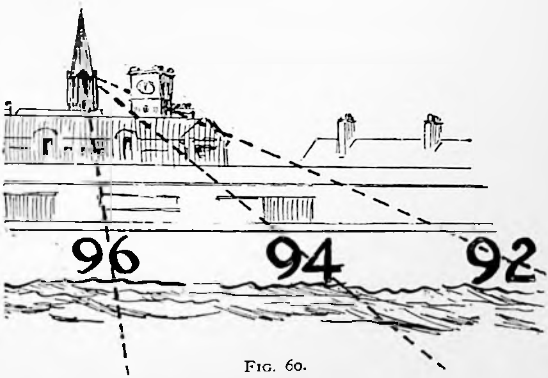


Fig. 60.

Professional adjusters utilise the courses steered, also transit bearings of numerous shore objects as seen from the ship when she is proceeding to the adjusting station. This they are enabled to do from their local knowledge and experience, the methods being really "tricks of the trade." When a ship is under way and proceeding down the Clyde from Glasgow, for example, the courses down the various reaches of the river vary from about N. by W. to W. by N., and by reducing the deviation when heading in this quadrant with the magnets and soft iron correctors, the directive force of the needle is made nearly the same on all headings, the card is, colloquially speaking, "licked into shape," and quickly comes to rest when the ship is being finally swung at the Tail of the Bank.

This saves much valuable time as it is only necessary to touch up the magnets and correctors a little to remove the small deviations which remain when the time comes to make the final adjustment.

When the bearing of a distant object cannot be found by any of the foregoing pre-arranged methods, a good working magnetic bearing of it may be obtained by taking the mean of its compass bearings as found on eight equi-distant headings, but obviously, this indirect method takes up a lot of time and, in consequence, is rarely adopted in the Mercantile Marine, where the operation of adjusting compasses must be performed with expedition and on a commercial basis; tugs and pilots are paid by the hour. But it may, on very rare occasions, be desired to study the magnetic condition of a ship by analysing the virgin deviations on an untouched compass, and apportioning to each disturbing force its approximate amount of deviation. This operation is carried out and recorded on the following lines.

Ship's head by compass.	Compass bearing of object.	Magnetic bearing of object.	Deviation.
N.	N. 42° E.	N. 45° E.	3° E.
N.E.	N. 62° E.	,,	17° W.
E.	N. 65° E.	,,	20° W.
S.E.	N. 60° E.	,,	15° W.
S.	N. 48° E.	,,	3° W.
S.W.	N. 35° E.	,,	10° E.
W.	N. 24° E.	,,	21° E.
N.W.	N. 24° E.	,,	21° E.
	8)360		
Magnetic Bg.	N. 45° E.		

Co-efficient *A* is the mean of the deviations on N., S., E., and W. and referring to the foregoing table, these are

(N) 3 E. (E) 20 W.
(W) 21 E. (S) 3 W.

$$24 \text{ E.} - 23 \text{ W.} = 1 \text{ E.} \therefore A = \tfrac{1}{4} \text{ E.} = + \text{A.}$$

Co-efficient *B* is the mean of the deviations on E. and W. with the name *changed* on west.

$$20 \text{ W.} + 21 \text{ W.} = \frac{41}{2} = 20\tfrac{1}{2} \text{ W.} = -\text{B.}$$

Co-efficient *C* is the mean of the deviations on N. and S. with the name *changed* on south.

$$3\text{ E.} + 3\text{ E.} = \frac{6}{2} = 3\text{ E.} = +C.$$

Co-efficient D is the mean of the deviations on N.E., S.W., S.E., and N.W. with the name *changed* on S.E. and N.W.

(N.E.)	17 W.	(S.E.)	15 E.
(N.W.)	21 W.	(S.W.)	10 E.

$$38\text{ W.} \quad - \quad 25\text{ E.} = \frac{13}{4} = 3\tfrac{1}{4}\text{ W.} = -\text{ D.}$$

Co-efficient E is the mean of the deviations on N., S., E., and W. with the name *changed* on east and west.

(N)	3 E.	(S)	3 W.
(E)	20 E.	(W)	21 W.

$$23\text{ E.} \quad - \quad 24\text{ W.} = \tfrac{1}{4}\text{ W.} = -E$$

94. Sea Methods.—There are usually two or more auxiliary compasses on board and, when these are fitted with binnacles to receive magnets and correctors, they may also be compensated at the same time as the standard when swinging ship. An assistant stands at each compass and on a pre-arranged signal being given by the adjuster working at the standard compass when the ship's head is, say, east magnetic, each assistant introduces a fore and aft magnet until his compass indicates ship's head east. Similarly, when her head is north magnetic the adjuster gives the signal and each assistant introduces an athwartship magnet until his compass also shows north. When ship's head is north-east the deviation is removed with the spheres, the whole process being similar to the methods adopted at a deviascope in a class room.

It may not be always possible to steady the ship's head in the magnetic direction required, especially at sea, perhaps for lack of a pelorus or sufficient assistance, so, under such circumstances, the ship's head is put on north by compass and the deviation noted in the usual way by observing the azimuth of the sun; an athwartship magnet is then placed in position to clear off the deviation, the compass north being thereby deflected away from the lubber line and brought nearer to magnetic north. The ship's head is again steadied on north by compass, the deviation is found to be less than before, so the magnet is moved closer to the compass and again the north moves away from the lubber line. The ship's head is steadied on north by compass repeatedly, the deviation found and again reduced with the magnet, until, finally, there is no deviation

left when the ship's head is north by compass which will now be north magnetic. Similarly, the ship's head is put on east by compass the deviation found and the fore and aft magnet placed in position to eliminate the deviation by progressive stages, and thus, by a process of trial and error the compass is corrected.

It may be necessary, on occasions, for navigational purposes, to find the deviation at a number of compasses placed at various positions on board ship. This may be done expeditiously by swinging ship and plotting the deviations of each compass on a Napier's diagram ; a curve drawn through the spots thus found, even though for irregular directions of ship's head, will form a complete curve of deviation for that compass. An observer is stationed at each compass, his job being merely to note the direction of the ship's head by his compass when the signal is given by the officer working at the standard compass, who notes, (1) head by standard compass, (2) compass bearing of object, (3) deviation at standard compass, (4) applies this deviation to head by compass to get head magnetic. Having completed the swing the magnetic heads are compared with the corresponding compass heads as noted for each compass, the differences between the two heads being the deviations at each compass respectively. The work might be tabulated as follows :—

	Observation at standard compass.				Magnetic head.	Compass No. 1.	
	Compass bearing of object.	Known mag. bearing of object.	Dev.	Head by standard compass.		Head.	Dev.
1	N. 32° E.	N. 30° E.	2° W.	North	N. 2° W.	N. 8° W.	6° E.
2	N. 30° E.	,,	0	N. 45° E.	N. 45° E.	N. 42° E.	3° E.
3	N. 27° E.	,,	3° E.	S. 90° E.	S. 87° E.	S. 87° E.	0
4	N. 29 E.	,,	1° E.	S. 45° E.	S. 44° E.	S. 40° E.	4° W.
5	N. 31° E.	,,	1° W.	South	S. 1° E.	S. 6° W.	7° W.

95. Tentative Adjustment is a Good Working System.—The method already described of compensating the compass experimentally is that practised by adjusters in the Mercantile Marine. It is a simple mechanical operation which can be expeditiously performed without any previous knowledge whatever of the ship's magnetic condition and gives satisfactory results. In ships of the Royal Navy the selection of a suitable position for the compasses presents

difficulties which are not experienced in ships of the Merchant Service, owing to the heavy masses of iron, such as guns, turrets and protective armour which enter into the construction of a "man o' war," so the following procedure is usually adopted when swinging ship for deviation and making a first compensation of the compass.

96. The Admiralty Procedure of Tentative Adjustment.—

1. The ship's head is steadied successively on N.E., S.E., S.W., N.W. The mean of the deviations found on these respective points with the signs changed at S.E. and N.W. gives an approximate value of coefficient *D*. Reference is then made to a table furnished by the Admiralty (*see* Appendix, Table IV.) which gives the sizes of soft iron spheres, and the distance they should be placed from the compass in order to correct various amounts of quadrantal deviation. Suitable spheres having been selected to correct the estimated *D*, they are then placed on the side brackets at the given distance.

2. The effect of the forces causing heeling error is now measured by means of the vertical force instrument and corrected with the vertical magnet as in par. 88.

3. The ship's head is now swung to the same direction as it was in the building yard. This eliminates the deviation caused by sub-permanent magnetism (*see* par. 58). The vertical iron is now the only force exerting a deflective influence on the needle, so any deviation appearing on the compass is corrected with the Flinders bar. If the direction of the building slip is not known, or the prevailing circumstances make it undesirable to place her head in this direction, or should the vessel have been built with her head on a cardinal point, the value of induced *B* is estimated from experience previously gained in a similar type of ship, and compensation made by an equivalent amount of Flinders bars as directed in another table issued by the Admiralty (*see* Appendix, Table VI.)

4. The semi-circular deviation due to hard iron, co-efficients *B* and *C*, is then corrected in the usual way, *B* with a fore and aft magnet when the ship's head is E. or W., and *C* with an athwartship magnet when her head is N. or S.

97. Order of Precedence.—Other factors being equal, the value of compass adjustment depends on the accuracy of the magnetic bearing of the distant object. The sun is the most reliable in this respect. The sun's true azimuth is taken from Burdwood's, Davis' or other Azimuth Tables for intervals of every four minutes covering

the period of time that will subsequently be occupied in swinging ship, and these true bearings are turned into their corresponding magnetic bearings by applying the variation for the place. Failing the sun the bearings of terrestrial objects are used, and, less frequently, the method of reciprocal bearings (par. 60, Chap. VIII.). Should, however, the prevailing weather or geographical conditions prevent the adjuster from employing the sun, or a shore object, he resorts to the use of an instrument called a deflector, which reveals changes in the directive force of the needle as the ship's head swings round.

98. The Principle of Adjustment by the Deflector.—The adjustment of the compass by the aid of a deflector is based on the principle that if the directive force of the compass needle is equal on the four cardinal points there can be no semi-circular deviation, and if the directive force, with the ship's head on N. and S. be equal to the directive force on E. and W. there can be no quadrantal deviation.

An ordinary magnet, fitted with a central cap so that it may lie horizontally on a vertical support in the centre of the glass cover of the compass bowl, makes quite a useful deflector, and this is the form of deflecting needle supplied with the deviascope to demonstrate the following system of adjustment.

99. The Deviascope Deflector.—1. The head of the model having been put on N. by *compass*, the deflector is placed in position on the glass cover with its S. pole over the N. point of the compass and then

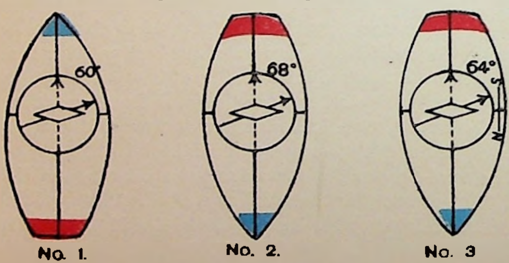


FIG. 61.

turned gradually in azimuth to the right or left—say to the right hand—until it is exactly at right angles to the fore and aft line, when the compass N., having followed the south end of the needle, will eventually come to rest pointing somewhere to the right of its

original direction. The angle through which the card has been thus deflected is noted, say 60° as in fig. 61, No. 1.

2. The deflecting needle is now removed and the model's head turned to S. by *compass*. The deflector is again placed in position on the compass bowl, and the card slowly deflected to the right hand, until it comes to rest, with the deflector again at right angles to the fore and aft line. The angular deflection is noted—say 68° as in fig. 61, No. 2—and, still keeping the deflector in position, a fore and aft magnet is introduced until the card shows a deflection of 64°, which is the mean between 60° and 68° (fig. 61, No. 3). This disposes of co-efficient *B*

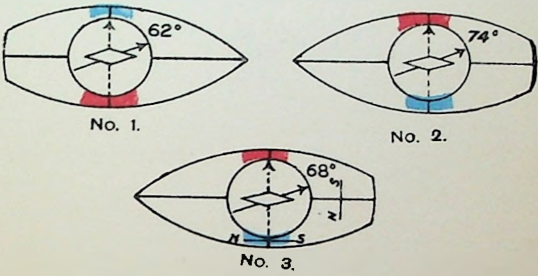


FIG. 62.

3. The head of the model is then steadied on E. by *compass*, the deflector laid over the needle and turned to the right hand until it lies exactly fore and aft, as in fig. 62, No. 1, and the angle through which the card has been deflected is jotted down, say 62°.

4. The deflector is now removed and the model's head steadied on W. by *compass*. The card is again deflected to the right hand by turning the deflector round until it lies exactly at right angles to the original direction of the needle, that is, at right angles to the athwartship line of the model. Suppose the angle of deflection to be 74°, (fig. 62, No. 2). The mean of 62° and 74° is 68°, so now, without removing the deflector, an athwartship magnet is placed in position to cause the card to show a deflection of 68° (fig. 62, No. 3). This disposes of co-efficient *C*.

5. The mean deflection for N. and S. was 64°, and for E. and W. 68°, and this difference indicates the existence of quadrantal deviation, a co-efficient $+D$, because the deflection on E. and W. is greater

than on N. and S., due to the induced magnetism in the athwartship beams diminishing the directive force of the needle on E. and W. The mean of the two means is 66°, so now, without the deflector having been removed, and with the model's head still on W., the soft iron spheres are placed on the brackets to make the card show a deflection of 66°.

100. Recapitulation.—The deflection on N. was 60°, on S. 68°, and the mean angle of 64° was obtained with a fore and aft magnet. The deflection on E. was 62°, on W. 74°, and the mean angle of 68° was obtained with an athwartship magnet. The mean of the two mean deflections, 66°, was obtained with the spheres.

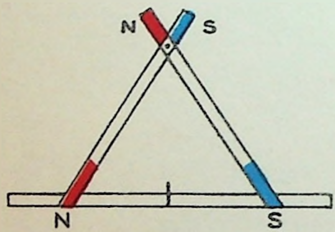


FIG. 63

101. Lord Kelvin's Deflector, fig. 64, is the instrument most commonly used by adjusters. It is more sensitive in its action than the single needle we have just described, and in the hands of an expert manipulator the deviation of the compass can be reduced to a degree or two. It, however, requires experience to keep the card steady during the critical period when it is being poised at the normal angle of deflection, but proficiency comes with practice.

The Kelvin deflector consists of two upright magnets having their unlike poles placed together, the upper ends being hinged like a pair of compasses, so that the lower ends can be opened and closed by means of the worm screw to which they are attached (figs. 63 and 64).

The magnetic power of the deflector is increased by lengthening the distance between the poles, and the object to be attained is to so regulate the power of the deflector that the card is swung through an angle of 90°, which is called the " normal deflection," the measure

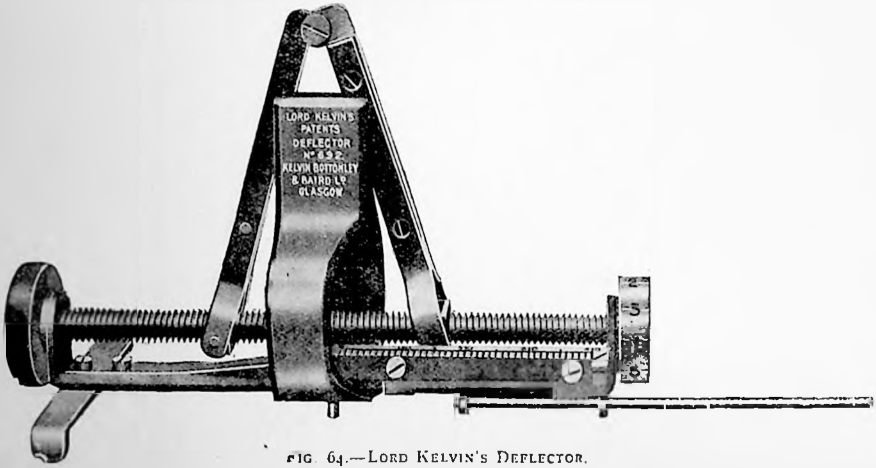


FIG. 64.—LORD KELVIN'S DEFLECTOR.

of the power necessary to do so being indicated by a scale of divisions on the instrument. The centre pin of the deflector fits into the cavity in the centre of the glass cover of the bowl which receives the pin of the azimuth mirror and it turns on this axis in precisely the same way.

102. Method of Using the Kelvin Deflector.—If shore objects suitable for adjusting the compass are not available, the ship is kept going as steady as possible by means of a steering compass, while the deflections are being made. It is the invariable practice to first compensate for estimated values of co-efficient D and induced B, and also for the heeling error before proceeding with the deflections. Perhaps a description of the following experiment which was performed on the roof deviascope, *see* frontispiece, will convey some idea of the method of using the deflector :—

1. The vertical iron usually placed near the compass to produce an induced B was removed from the model, as this disturbing force is corrected approximately with the Flinders bar before beginning the operation under actual ship conditions.

2. It was estimated that the soft iron beams introduced into the model would produce a $+D$ of 4°, and this amount of quadrantal devi- tion was corrected with a pair of 6-inch spheres placed close up to the compass as directed in Table IV. in the Appendix.

3. The heeling error instrument (*see* fig. 57) was then placed in the position occupied by the card, the bowl being removed temporarily to admit of this being done, but no appreciable effect of vertical force was detected so no compensation was made. The only disturbing force now left on the model being hard iron, producing co-efficients B and C, we proceeded as follows :—

4. The head of the model was steadied on N. by compass, the deflector placed in position on the glass cover, then, with its pointer over the north point of the card, the poles were opened out and the instrument turned to the right, the card meanwhile following the deflector, until by a little manipulation of the screw which regulates the distance apart of the poles, and jockeying the instrument with its pointer over the E. by N. point of the compass, the card was brought to rest at the normal deflection of 90°. The scale reading was 11.7. The deflector was then eased back, lifted off, and the card came to rest at N.

5. The head of the model was now turned to E. by compass and

the foregoing operation repeated, the normal deflection, that is the compass card deflected to an angle of 90° with the pointer of the deflector over the E. by N. point of the compass, was obtained when the scale indicated 8.0. The deflector was eased back, lifted off, and the card came to rest at E.

6. With the model's head on S. by compass the normal deflection was obtained with a scale reading of 8.2.

The mean for N. and S., namely, $\frac{11.7+8.2}{2}$ being 9.95, the instrument, without removing it from the bowl of the compass, was set to this division on the scale. This increased its magnetic force and caused the card to leave the normal but, by manipulating the deflector and inserting magnets in the fore and aft holes in the binnacle, the normal deflection was again restored with the pointer exactly over the E. by N. point. The deflector was then removed.

7. With head on W. by compass, the normal deflection was got when the scale showed 13.0. The readings for E. and W. being 8.0 and 13.0, the poles of the deflector were closed a little until the scale indicated the mean reading of 10.5. Once more with a little manœuvring of the instrument, and inserting magnets in the athwartship holes of the binnacle, the normal deflection of 90° was again obtained with the pointer of the deflector over the E. by N. point of the card.

The scale readings were then discussed as follows :—

Head north - -	11.7	Head east - -	8.0
„ south - -	8.2	„ west - - -	13.0
mean - -	9.9	mean - -	10.5

The difference between the two mean readings being only 0.6 divisions demonstrated that co-efficient *D* had been closely corrected with the spheres.

A disadvantage of adjusting by the deflector is the fact that a table of deviations cannot be supplied. The adjuster can merely claim that the residual deviations are small and he may even define certain limits but, obviously, the degree of accuracy depends on the expertness of the manipulator.

To test the accuracy of the work in this case the model was swung before, and after, adjusting the compass by the aid of the deflector, and the deviations found by means of the known magnetic bearing of a distant object. The original deviations varied from 17° E. to 11°

W. but after the compensations were made the deviation on any point did not exceed one degree.

Such a close degree of accuracy could scarcely be expected in actual practice owing to the irregular distribution and varying intensity of the magnetic forces on board ship, whereas, on the model, the disturbing forces were simple in character, being merely hard and soft iron symmetrically distributed round the compass.

103. Vibrating Needles.—The magnetic intensity of the earth and of the ship relatively to each other may be determined by the oscillations of a needle, mounted so as to vibrate either in a horizontal or a vertical plane. A vibrating needle is just a flat magnet about 3 inches long, and pointed at each end, the horizontal needle being fitted with a jewelled cap and supported on a pivot in the same way as the compass needle ; in fact, the compass card itself would serve the same purpose fairly well, while the vertical vibrations could be made with the vertical force instrument used for the heeling error (fig. 57).

104. Method of Measuring the Magnetic Force of a Ship.—The vibrational activity of the needle increases when the magnetic intensity increases. Suppose at a certain position in the ship the horizontal needle made 10 vibrations in 60 seconds, and at another position on board it required only 50 seconds to make the same number of vibrations, then the intensity is greater at the second position than at the first, because the same number of to and fro movements have been performed in less time.

If, at a third position, the needle takes 70 seconds instead of 60 seconds to make 10 vibrations, it indicates that the magnetic intensity is diminished, the needle now being slower in its movements. It was by means of such experiments, carried out on board a number of ships when they were first launched, and again, after they had made several voyages in both hemispheres, that the Liverpool Compass Committee analysed the magnetic condition of an iron ship. Horizontal and vertical vibrational tests were made at numerous positions in and around the hull to discover the intensity and distribution of the polarity in the ship. Compasses were also placed at different positions on board, the deviations being recorded under various conditions of trim, course, place and time. The results of the investigation, conducted over a period of years, enabled the Committee to establish the laws governing the deviation of the

compass and its compensation (the Report of the Liverpool Compass Committee to the Board of Trade, 1855 and 1856).

105. Coefficient λ (*Lambda*) is the ratio the mean horizontal directive force of the compass needle on board bears to its horizontal directive force on shore. It varies inversely as the square of the times occupied by a needle in making an equal number of vibrations on shore and on board.

The ship's force may act with, or against, the earth's force depending on how the ship is heading, thus increasing the mean directive force of the compass in the former case and reducing it in the latter. The magnetic effect of the ship and earth combined is determined as follows:—

106. How to Find Lambda.—1. At a position on shore, free from local attraction, deflect a horizontal needle about 40° and release it; note the time it takes to make a certain number of vibrations—say 10 in 60 seconds.

2. Go on board the ship, lift off the compass card, and place the same needle in the bowl, using the same pivot as on shore. Deflect the needle, and suppose it makes 10 vibrations in 50 seconds then,

$$\frac{\text{H.F. on board}}{\text{H.F. on shore}} = \frac{(\text{time on shore})^2}{(\text{time on board})^2} = \frac{60^2}{50^2} = \frac{3600}{2500} = \frac{1.44}{1}$$

This indicates that the directive force of the needle, for the direction of ship's head at the time, has been increased viz., 1.44, the directive force on shore being taken as unity. The ship's force has, in this case, been allied with the earth's force.

If the needle had occupied 70 seconds in making 10 vibrations on board, then,

$$\frac{\text{H.F. on board}}{\text{H.F. on shore}} = \frac{60^2}{70^2} = \frac{3600}{4900} = \frac{.73}{1}$$

showing that the directive force is now only .73 of that on shore, so that the ship's force, for this direction of her head, is antagonistic to the earth's force.

These values have to be multiplied by the cosine of the deviation for the ship's head and the mean of all the results found on equidistant courses during a complete swing is co-efficient λ (Lambda).

The value of λ at a well placed compass is about .9 usually, the diminution of the mean directive force being due to the induced magnetism in continuous horizontal beams acting on the needle in opposition to the earth's force. A knowledge of the value of Lambda

is important when selecting a suitable position for the compass, because the deviations are increased when the directive force of the needle is weakened, the needle being then less able to resist the disturbing effect of the ship's magnetism. It is desirable, for this reason, to place the compass where the value of λ is found to be greatest.

107. Co-efficient μ (Mu) is the ratio of the mean value of the vertical magnetic force at the compass to the vertical magnetic force on shore.

It is found in a similar manner to Lambda, only the vibrations are made in the vertical plane instead of the horizontal. These co-efficients enter into some of the mathematical investigations connected with deviation, many of which are highly theoretical and have no place in practical navigation.

The value of Mu may be found by means of the dip circle (fig. 87) as follows:—The dipping needle on shore when in the magnetic meridian lies in the line of dip, but if turned round out of the meridian the dip will apparently increase until the needle stands vertical which it will always do when at right angles to the meridian, as it is then only acted on by the earth's vertical force, the supporting pivots preventing any horizontal action. Suppose the needle when in this position on shore is vibrated through an angle of about 20° on each side of the vertical and that it makes 10 vibrations in 12 seconds. Now mount the same dip circle in the binnacle on board so that the centre of its needle shall occupy the same place as the centre of the compass needles. Turn the dip circle round until its needle stands vertical, then vibrate it and suppose it makes 10 vibrations in 15 seconds then

$$\frac{\text{V.F. on board}}{\text{V.F. on shore}} = \frac{(\text{time on shore})^2}{(\text{time on board})^2} = \frac{(T)^2}{(T')^2} = \frac{12^2}{15^2} = .64.$$

This indicates that the vertical force on board ship is weaker than the vertical force on shore which is unity, and that a red pole predominates below the compass which, being an upward thrust, will push the needle to low side when the ship heels. When the value of the vertical force is greater than unity it indicates that a blue pole predominates below the compass which will draw the needle to high side when the ship heels.

Co-efficient Mu is the mean vertical force as found on equidistant headings, but when the ship's head is east or west

$$\text{Mu} = \frac{(T)^2}{(T')^2}$$

because on this heading fore and aft horizontal iron is in its neutral

position. Should the vibrations be made on a heading other than east or west co-efficient Mu will be the mean vertical force as found on two opposite points, because then the vertical effect of fore and aft iron will cancel itself. (See fig. 66). Mu is therefore due to the vertical components of sub-permanent magnetism and vertical iron acting on the compass and its value is different at each compass.

108. **Heeling Error Constant.**—It might here be remarked that when the vertical force instrument is horizontalised on shore for the specific purpose of correcting the heeling error, the sliding weight should be altered a little (usually inwards) by an amount equal to λ (1 — Nat. sine coeff. *D*), when the adjustment is made before the spheres are placed in position. This quantity is known as the heeling error constant and its value is computed for each compass. It is due to the fact that magnetic needles are weaker on board than on shore. There would be no constant if the mean horizontal force on board were the same as the horizontal force on shore, that is to say lambda$=1$, and this should be the case in a ship having no horizontal beams, for then co-efficient *D* would disappear from the above equation. These beams, however, not only cause quadrantal deviation but also weaken the intensity of the dip needle, with the result that if the needle were balanced exactly on shore and then placed in the binnacle on board it would be found, neglecting for the time being the dipping effect of the ship's polarity below the compass, that the needle would be no longer horizontal, it would be overbalanced and the north end would point slightly upwards, due *solely* to the diminution of the magnetism in the needle caused by the horizontal beams.

It would be possible to bring the needle back into the horizontal plane in one of three ways: (1) by removing the horizontal beams without disturbing anything else, if it were possible to do so; (2) by placing the quadrantal correctors in position and so correcting co-efficient *D*, which, of course, would counteract the cause of the trouble; (3) by sliding the weight inwards until by trial and error the needle is made horizontal.

The first suggestion is absurd, the second is the simple and obvious thing to do. The third suggestion is, however, not so easily carried out because the dip of the needle on board registers the joint effect of the ship's polarity below the compass and the loss of magnetism due to the beams, the heeling error constant being a measure of the latter only.

The constant λ ($1 -$Nat. sine co-eff. D) expresses mathematically the difference between the magnetic intensity of the needle on board and on shore, and the action of moving the sliding weight inwards by an amount got by means of this multiplier is merely adjusting the needle for its temporary loss of magnetism.

When the spheres are placed in position to compensate co-efficient D they restore the loss of magnetism due to the athwartship beams and the value of the constant is correspondingly reduced, the residual effect, if any, being caused by any horizontal iron that may be acting but not compensated by the spheres. The new value of Lambda after the spheres are in position is called λ_2 to distinguish it from the original lambda. It is, therefore, obviously desirable to compensate quadrantal deviation before adjusting for heeling error by means of the vertical force instrument.

EXAMPLE:—Suppose $\lambda = .9$, the quadrantal deviation $D = 4°$, and the scale reading on shore 20; find the modified reading to which the sliding weight should be placed on the vertical force instrument before compensating the compass for heeling error.

$$\begin{aligned} \text{The heeling error constant } &= \lambda\ (1 - d) \\ &= .9\ (1 - \text{nat. sine } 4°) \\ &= .9\ (1 - .07) \\ &= .9 \times .93 \\ &= .837 \end{aligned}$$

The modified reading = shore reading $\times$ constant.

$$\begin{aligned} &= 20 \times .837 \\ &= 16.74 \end{aligned}$$

The heeling error constant, or multiplier as it is sometimes called, depends on λ and co-efficient D, and as these differ in amount at different compasses it is obvious that each compass must have its own constant. Nor is its value readily found, and as the preliminary information is seldom available, the practical adjuster, instead of shifting the weight one-tenth inwards when compensating heeling error, sometimes raises the vertical magnet until the north end of the vertical force needle points slightly upwards.

Owing to the method adopted by some makers of fitting the suspension of the bowl higher than the plane of the compass needles, it is found that the needles swing out to one side of the line drawn between the correcting magnet and the centre of the suspension system when the ship heels, thus causing the curved lines of force from the magnet to pass more horizontally through the needle than

desired (fig. 65). This condition is remedied by lowering the bucket containing the vertical magnets about 1½ inches below the height which is necessary to make the needle of the vertical force instrument point slightly upwards.

109. Unadjustable Heeling Error.—A heeling error may also be caused by fore and aft horizontal iron when the end of it is immediately above or below the level of the compass. No practical method of compensating this portion of the error has been devised,

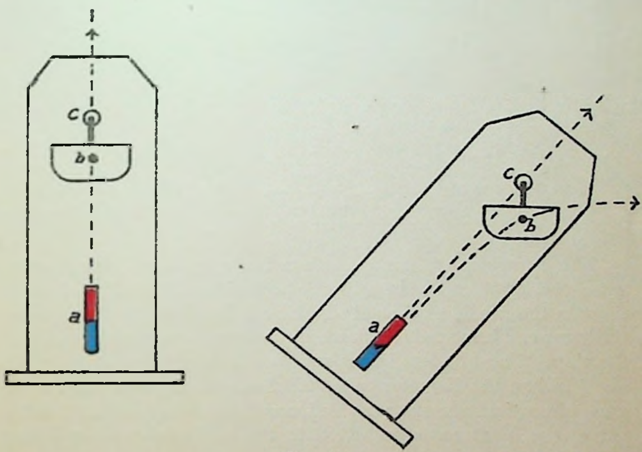


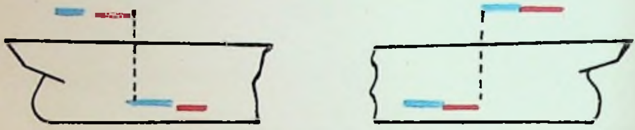
Fig. 65.

Ship upright.
a The vertical magnet.
b The compass needle.
c The centre of suspension.

Ship heeled.
a c A straight line of force.
a b A curved line of force passing through the needle at *b*.

owing to the fact of the polarity changing in the fore and aft iron when the ship's head is reversed, thus causing the needle when attracted to the high side on northerly courses to be attracted to the low side on southerly courses (fig. 66).

The ship's head for this reason should be kept near east and west when manipulating the vertical magnet, in order to bring the fore and aft iron into its neutral position at right angles to the meridian, and thus eliminate its effect from the vertical force instrument for the time being.



Head North. Head South.

Needle drawn to high side. Needle drawn to low side.

FIG. 66.

The Flinders bar partly assists in correcting heeling error, when the lower end swings to the high side of the vertical plane through the needle as the ship heels and, in the north hemisphere, the lower end being red it repels the compass north to the low side of the ship. The Flinders bar is supplied in lengths of 12, 6, 3, $1\frac{1}{2}$, and $\frac{3}{4}$ inches, the diameter being 3 inches, and pieces of wood of the same dimensions are also provided, so when a length of bar is taken out of the brass container fitted to the binnacle a corresponding piece of wood is put in its place, the object being to maintain the total length at 24 inches, the top end of the bar being kept slightly above the level of the needles, about one-twelfth of its length. Six inches of Flinders bar means a piece of malleable iron 6 inches in length resting vertically on 18 inches of wood.

QUESTIONS.

1. Describe briefly the procedure of adjusting the compass usually adopted in ships of the Royal Navy. (96)

2. What is the principle which governs the operation of adjusting the compass with the aid of the deflector? (98)

3. Describe how the compass on Beall's Deviascope is adjusted by deflections. (99)

4. Describe the operation of using Lord Kelvin's Deflector when adjusting the compass. (102)

5. What is the disadvantage of adjusting by means of a deflector ?

6. How may the magnetic force of a ship relatively to the earth's force be measured ? (104-106)

7. Define co-efficient λ (Lambda) and explain how its value is found. (105)

8. What is co-efficient μ (Mu) ? (107)

9. What steps should be taken to ascertain if the compass you are to adjust is in order ? (93)

10. How may the magnetic bearing of a distant shore object be found? (93)

11. How are the co-efficients A, B, C, D and E calculated from the deviations of an untouched compass ? (93)

12. Describe the process of finding the deviations at two or more compasses placed at different positions when swinging ship. (94)

13. Why should the north end of the vertical force instrument point slightly upwards when adjusting for heeling error ? (108)

14. What is meant by the "heeling error constant" ? (108)

15. When heeling error is corrected with ship upright why should the vertical compensating magnet be lowered about 1½ inches ? (108)

16. Why should the ship's head be kept near east or west, if possible, when using the vertical force instrument ? (109)

17. What is meant by saying "nine inches of Flinders bar" and at what height should the top end be ? (109)

18. State Ampere's rule regarding the effect of a current of electricity on a compass needle. (Page 136).

19. What position will a properly mounted dipping needle take up when turned at right angles to the magnetic meridian, and give reasons for saying so ? (107)

20. Why should Flinders bar and spheres be placed in position before correcting heeling error ?

21. Show by sketches why heeling error due to soft vertical iron under the compass cannot be compensated by soft vertical iron above the compass.

CHAPTER VIII.

110. A " **Deviascope** " is an instrument by means of which the effect of ship magnetism on the compass can be demonstrated.

The most popular model is Captain Beall's " Compass Deviascope," which now forms part of the equipment of all navigation schools and examination rooms. (*See* fig. 67.) It consists of a flat board, which is so mounted on a central axis that it can be freely rotated and heeled over to any desired angle. This axis is stepped on a foundation board, which forms a " dumb " compass card, the north and south points of which are set in the plane of the magnetic meridian. A brass pointer, representing the fore and aft line of the ship, is attached to the vertical axis and rotates with the model, so that the magnetic direction of the ship's head can be read off on the dumb card underneath.

The difference between the magnetic direction indicated by the pointer and the ship's head as shown by the deck compass is the deviation.

Thirty-two grooves, one for each point of the compass, and all intersecting over the vertical axis, are scored into the deck, the fore and aft and the athwartship grooves being distinctively marked as the correcting magnets have to be placed thereon. The radial grooves are intended to receive magnets to represent the sub-permanent poles of the ship, the positions of which are determined by the direction of her head whilst building.

A couple of athwartship beams, numbered 3 and 3 in fig. 67, are slipped into receptacles under the deck, and brackets to receive the compensating spheres for same (Nos. 9 and 10) are attached to the mountings of the compass. A removable vertical bar, No. 5, is shown abaft the compass, with which is associated a Flinders bar, No. 6. In the upright brass tube on the under side of the deck, No. 12, is placed a magnet to represent the vertical force of the ship which causes heeling error, this being counteracted by means of the vertical magnet, No. 13, under the centre of the compass.

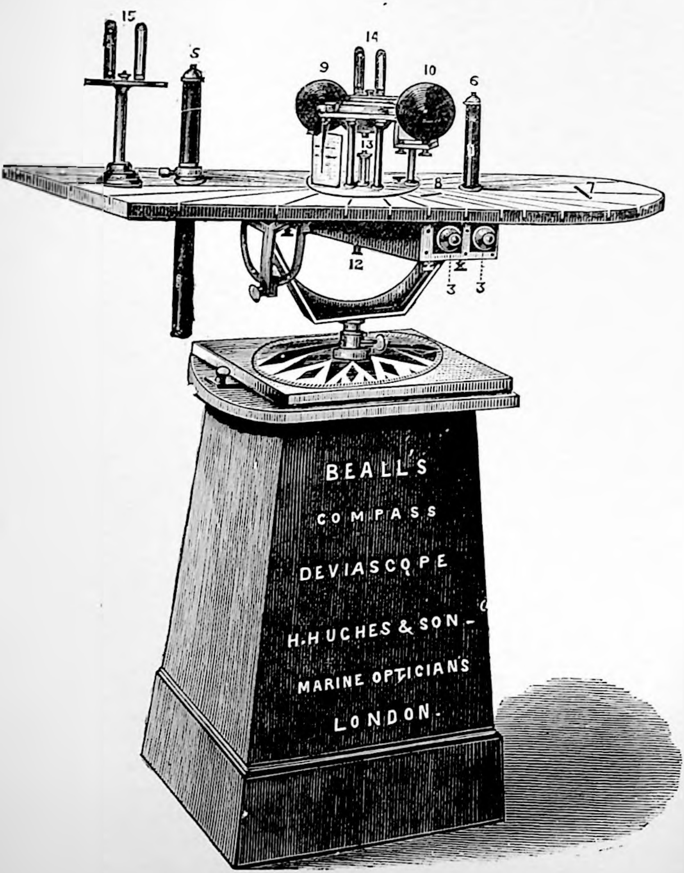

15
5
14
9
10
6
13
8
7
12
3
3
BEALL'S
COMPASS
DEVIASCOPE
H. HUGHES & SON
MARINE OPTICIANS
LONDON.

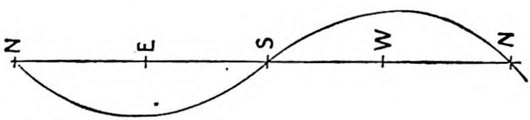
FIG. 67.

It is impossible to give a written description explanatory of the arrangement and working of this instrument, which will convey as much practical information as can be imparted by actual demonstration at the deviascope. If the student, however, will now try and conceive himself to be standing at the stern of the model in fig. 67, and exercise freely his powers of imagination by accepting the diagrams which accompany the following discussion as representing the deviascope, he should be able to attain a fairly good conception of the method of tentatively adjusting the compass as practised in ships of the Merchant Service.

111 **A Demonstration at the Deviascope** affords an excellent opportunity of studying the deviations produced by the three principal disturbing forces into which the total magnetic force of a ship has been conveniently resolved, namely, the effect arising from sub-permanent magnetism, from vertical iron, and from horizontal beams.

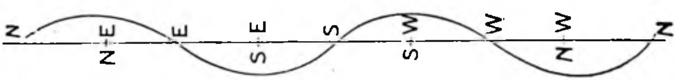
It is an interesting and instructive experiment to test the effect of each force separately by swinging the model and plotting the resulting deviations on a Napier's diagram.

If, for example, the vertical bar No. 5, fig. 67, is placed abaft the compass, the deviation found will be zero when the model is heading N. and S., increasing to a maximum when heading E. and W., thus demonstrating clearly a semi-circular deviation, a $-B$ curve.



A Semi-Circular Curve—*B*.

When swung with the transverse beams only in position the deviation will be found to change its name in alternate quadrants, being zero on the cardinal points, and attaining its maximum on the inter-cardinal points, a $+D$ curve.



A Quadrantal Curve $+D$.

The curve arising from the horizontal component of the ship's sub-permanent magnetism is semi-circular in shape, but the points on which the maxima and minima occur depend on the direction of the ship's head whilst building. The effect can be illustrated on the model by placing a long single magnet in the plane of the magnetic meridian passing through the ship during construction.

If, for example, we wish to illustrate the effect of ship's head north in building yard, the magnet would be laid in the fore and aft midship groove, with its red pole at the bow and blue pole at the stern; if head east in building yard, the magnet would be placed in the athwartship groove, its red pole to port and blue pole to starboard; if N.E. in building yard, then place it in the fourth radial groove, red pole on port bow, blue pole on starboard quarter; if N.N.W., then in the second groove, red pole on starboard bow, blue pole on port quarter, and so on for any particular direction desired. But no matter how the model's head may have been in building yard, it will be found, on swinging for deviation, that the curve due to sub-permanent magnetism alone is semi-circular in shape, the deviation disappearing when the head of the model is in the same, or in the opposition direction to that selected for demonstrating her head whilst building, and attaining a maximum when at right angles to that direction; for example, if her head has been N.N.W. when building, the deviation on the compass will be zero when the model is heading N.N.W. and S.S.E. magnetic, and a maximum on E.N.E. and W.S.W. magnetic.

Two magnets, one painted red, the other blue, are provided with the deviascope, and these magnets are placed in their particular grooves, opposite to, and end on to, each other, one on each side of, and equi-distant from, the compass, to represent the magnetic axis of the ship, care being taken to keep the north or marked end of the red magnet and the south end of the blue magnet next to the compass. This arrangement produces very conveniently an effect similar to that of a long single magnet.

A student's practical knowledge of compass deviation is tested usually at the deviascope by questions similar to the following, which are based on the substance of the lectures given in the previous chapters, and perhaps the form of question and answer may appeal to those who prefer this method of acquiring knowledge.

The disturbing forces, namely, sub-permanent poles, vertical iron, transverse beams, and vertical magnet, having been placed into

position the student may be asked how the ship's head was supposed to have been in the building yard? He should then look in the grooves for the sub-permanent magnets, and note the colour of the pole which lies next to the compass in the fore part of the model.

Suppose a blue pole is found in the fourth groove on the starboard bow as in fig. 68, No. 1. This gives the direction of south magnetic when the ship was on the stocks, because the sub-permanent poles are

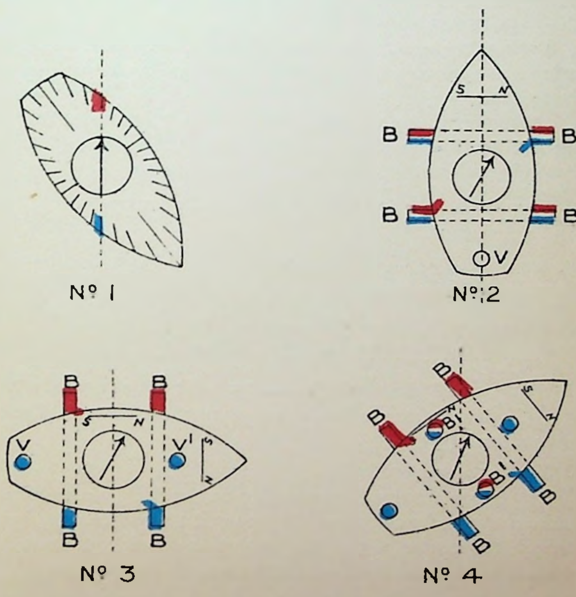


FIG. 68.

always fixed in the plane of the magnetic meridian passing through the ship at that time. Her head is four grooves, four points, to the left of south, therefore the ship's head was S.E. in the building yard.

1. What co-efficients will this produce?

Attraction being to the bow $+B$, and attraction to starboard $+C$.

2. When would you expect the greatest amount of deviation from sub-permanent magnetism?

When the ship is heading at right angles to the direction she lay in during construction, about N.E. and S.W. in this case. (58)

3. What is the first thing you would do towards getting this compass adjusted?

Look at the clinometer to ensure that the model is upright, then swing her head on north magnetic as shown by the pointer of the dumb card.

Refer now to fig. 68, No. 2, which shows the model heading N. and the needle drawn to starboard before the correcting magnet is placed in position.

4. To which side is the compass north drawn?

To starboard.

5. What deviation is there?

So many degrees east.

6. How do you know it is east?

Compass N. lies to the right of magnetic N.

7. What co-efficient is this, and what is it caused by?

$+C$, due to the athwartship component of sub-permanent magnetism. (57)

8. How is it corrected?

By placing a magnet athwartship on the deck, red or N. pole to starboard, with its centre on the fore and aft vertical plane passing through the centre of the compass, then moving it towards the compass until the deviation is cleared off.

9. Would you expect a deviation to appear at any subsequent time when the ship's head is north?

Yes, when the model is heeled over. (81)

10. What is the next step?

Steady ship's head on E. or W. magnetic. Refer now to fig. 68,

Note.—The number at the end of an answer refers to a previous paragraph in which a fuller explanation is given.

No. 3, which shows the model heading E. with the needle deflected forward before the correcting magnet is placed in position.

11. How is the north point of the compass drawn?

To the bow.

12. What do you make the deviation?

So many degrees east.

13. What kind of deviation is this?

Semi-circular.

14. What co-efficient is it?

$+B$.

15. Name the deviation arising from $-B$.

W. deviation on easterly courses, and E. deviation on westerly courses. No deviation when ship's head is north or south. (55)

16. Why is B greatest when ship's head is E. or W?

Because the fore and aft disturbing forces are then at right angles to the compass needle.

17. What is producing this deviation?

The fore and aft component of sub-permanent magnetism, also transient induced magnetism in vertical iron abaft the compass. (55)

18. How is the polarity distributed in the vertical iron, and what deviation is it causing in fig. 68, No. 3?

A blue pole in the upper half, attracting the needle to the stern of the ship, giving a W. deviation. (*See* also fig. 42.)

19. Explain why an E. deviation is appearing on the compass.

Because the sub-permanent attraction to the bow, in this case, happens to be greater than the attraction of the vertical iron to the stern.

20. Is there any difference between the semi-circular deviation produced by these two forces?

Yes, the deviation due to hard iron decreases slightly on approaching the equator, but that due to soft iron varies as the vertical force and decreases with the latitude, vanishes on the equator and changes name in the opposite hemisphere.

21. How should each of the two parts be compensated?

Sub-permanent B with a magnet placed fore and aft on the deck,

with its centre on the athwartship vertical plane passing through the compass, and induced B with a Flinders bar (V^1) placed on the fore side of the binnacle (fig. 68, No. 3; fig. 67, bar 6). (62-65)

22. In what way could you arrive at the amount of deviation produced by each?

Enter traverse tables with the direction of ship's head in building yard as a course, the value of co-efficient C in a departure column, and the value of sub-permanent B will be found in the difference of latitude column. The difference between the total B found when ship's head is east, and the sub-permanent B got from the tables, is the amount of induced B to be corrected with the Flinders bar.

23. Any exception to this Traverse Table rule?

Yes, it fails if the ship's head has been N. or S. whilst building, as no co-efficient C is then produced with which to enter the tables.

24. If you did not know the direction of the ship's head whilst building, what would you do?

Assume induced B to be about 4 or 5 degrees, as this is about its value in ordinary merchant ships.

25. How would you correct co-efficient *B* if the model were taken to the equator and brought back here again?

At the equator I would correct the whole deviation with the fore and aft magnets, then when I got back here I would correct any additional B with a Flinders bar.

26. Would this compensation remain perfect in all latitudes?

It ought to, because the effect of the Flinders bar and of vertical iron should vary in the same ratio, and if the magnetic intensity of the sub-permanent magnetism and of the fore and aft correcting magnet does not change the compensation should hold good for all latitudes.

27. What is the next process towards getting the compass adjusted?

Steady ship's head on one of the inter-cardinal points, say N.E., and test the compass for quadrantal deviation. Refer to fig. 68, No. 4, and observe that the port ends of the athwartship beams are pointing northward and have acquired red polarity.

28. Any deviation?

Yes, so many degrees east—co-efficient $+D$.

29. What is causing this deviation?

Transient induced magnetism in continuous transverse beams,

but fore and aft horizontal beams divided at the compass would also produce $+D$.

30. How is this deviation corrected?

By two soft iron spheres, one on each side of the binnacle, having their centres in the same horizontal plane as the needles, and placed equi-distant from the centre of the compass. Move the spheres towards the compass until the deviation is cleared off, then clamp them in position (fig. 67, spheres 9 and 10).

31. Describe the arrangement of iron which will produce a $-D$, and how it could be corrected.

$A -D$ is caused by divided athwartship beams and continuous fore and aft beams. It could be corrected by placing the spheres fore and aft.

32. Why is a $-D$ of rare occurrence in a ship?

Because there are comparatively few divided beams in a ship so that the effect of continuous athwartship beams usually predominates.

33. State the signs and effects of co-efficient D.

Co-efficient D gives greatest deviation when heading N.E., S.E., S.W., and N.W., decreasing to zero on N., E., S., and W.

$+D$ gives E. deviation when the ship's head is in the N.E. and S.W. quadrants, and W. deviation when in the S.E. and N.W. quadrants.

$-D$ gives deviation of an opposite name in these respective quadrants.

34. If the spheres are placed in their proper positions will D remain compensated in all latitudes?

Yes, because the beams and spheres cause a deviation equal in amount but opposite in name, and as each derives its magnetic effect from the earth's horizontal force, the ratio between them remains the same, and so the deviation will be corrected in all latitudes.

Again refer to figure 68.

No. 1 shows the ship's head S.E. in building yard, a blue pole being generated four points on the starboard bow, and a red pole four points abaft the port beam. These poles are permanently fixed in position.

No. 2 represents the same ship heading N. magnetic when adjusting the compass. The beams B B and vertical iron V do not produce deviation when ship's head is N. or S. as

their poles are acting parallel to the axis of the needle, but the compass N. is drawn to the right hand by the blue sub-permanent pole on the starboard bow, and this deviation (co-eff. *C*) is corrected with the athwartship magnet having its north pole to starboard.

No. 3 shows the ship's head E. magnetic, the beams are not causing deviation, but the blue pole in the vertical iron *V* is attracting the needle towards the stern, its effect being counteracted by the Flinders bar V^1 placed on the fore side of the compass. At the same time, the blue sub-permanent pole at the starboard bow is causing an E. deviation (co-eff. *B*) which is corrected with the fore and aft magnet, having its north pole forward.

No. 4 represents the ship's head N.E. The only disturbing force left uncorrected is the beam *B B*. Note the red pole in the port end repelling the compass N. to the right. This deviation is compensated by the soft iron spheres B^1 and B^1.

35. Are there any other co-efficients?

Yes; co-efficients *A* and *E*.

36. Assuming there was a co-efficient *E* on the compass how could it be corrected?

By slueing the spheres to an angle of 45° with the fore and aft line.

37. Describe co-efficient *A*.

It represents a deviation constant in name and amount for all directions of the ship's head. It is an index error, really, and may be due to the card not being accurately centred or graduated, the axis of the needles not being parallel to a line drawn through the N. and S. points of the card, the lubber line misplaced, or an error in computing the magnetic bearing of the object used in adjusting the compass. (78)

38. If I placed beams diagonally across the deck, what co-efficient would be reproduced?

Co-efficient *E*, which gives a maximum deviation when the ship's head is N., S., E. and W. decreasing to zero on N.E., S.E., S.W. and N.W. (71)

39. Why are the two co-efficients *A* and *E* not compensated?

Because the deviation arising from them should be small. If a decided *A* appeared on the compass I would first make sure that the lubber line represented accurately the direction of ship's head. If it still persisted I would get another compass card.

40. Would the compensation for the old card do equally well for the new one?

Yes, because the magnets and soft iron correctors are placed in position to counteract the ship's force. They protect the compass from the disturbing influence of the ship's magnetism, and unless the ship's lines of force break through this magnetic barrier, the compensation should do for any card placed in the same binnacle.

41. If the ship's head is swung rapidly, what co-efficient appears?

A temporary $-A$ when swung to port, and a $+A$ when swung to starboard, due to the card being carried round in the direction of ship's head by friction between the cap and the pivot.

42. Is the compass now satisfactorily adjusted?

There may be slight deviations left. I would now swing the ship's head on W. magnetic, and if any deviation appeared I would correct for half of this residual B, by moving the fore and aft magnet; then put her head on S.W. magnetic, and correct half of any residual D, by moving the spheres; then on S. magnetic, and correct half of any remaining C, by moving the athwartship magnet. The object in view being to equalise as closely as possible the directive force of the compass needle on all courses.

43. If the ship is heeled over, what co-efficient is affected?

Co-efficient C. (81)

44. How is the heeling error corrected?

Steady the ship's head on N. by *compass*, then heel the model. If the north point is drawn to the high side, insert the vertical magnet in the receptacle under the centre of the compass, red pole uppermost, until the compass N. points to the lubber line. But if the needle is drawn to the low side, keep the blue pole of the magnet uppermost. The model might then be heeled to the opposite side, and half of any remaining error corrected by raising or lowering the magnet (fig. 55, No. 3; fig. 67, corrector 12).

45. What causes heeling error?

The sub-permanent poles of the ship, also the induced poles in vertical iron and in transverse beams, all changing their position relatively to the compass needle when the ship heels.

46. What arrangement of these three forces will draw the compass north to the high side in the north hemisphere?

(1) The blue sub-permanent pole being nearer to the compass

than the red (2) vertical iron below the level of the compass, and (3) a continuous athwartship beam (fig. 55).

47. How may the needle be drawn to the low side?

By reversing the foregoing arrangement, namely, the red sub-permanent pole predominating on the compass, the top end of vertical iron extending above the level of the compass and a divided athwart ship beam (fig. 56).

48. Do the soft iron correctors diminish or increase the amount of heeling error?

The spheres reduce the error by correcting that part due to the athwartship beams, but the Flinders bar, if higher or lower than the card, may increase it, hence the desirability of having the upper pole of the bar at the same level as the compass card. (90)

49. Will the compensation for heeling error hold good for all latitudes?

No, because that part of the heeling error due to vertical iron decreases on approaching, vanishes at, and increases with a changed name on crossing, the equator, while the vertical magnet corrects for the same amount in all latitudes. (89)

50. Does the heeling error arising from sub-permanent magnetism remain the same?

No; it is least at the equator and greatest at the poles, but as it never decreases to zero, it cannot change its name on crossing the equator.

51. What is the explanation of this?

The sub-permanent force is assumed to remain the same, but the directive force of the compass needle increases on approaching the equator, and so becomes increasingly difficult to deflect. (92)

52. Must the ship be heeled to correct the heeling error?

No, it can be compensated by means of the vertical force instrument. (87)

53. Describe how you would go about this job.

I would take the instrument to a place on shore free from local attraction, suspend the needle in the magnetic meridian, and make it lie horizontal by moving the sliding weight. Then go on board, unship the compass card and place the instrument in the same position as the card occupied. Should the north end of the needle dip downwards it shows there is a blue pole somewhere below the

compass, and I would then insert the vertical magnet in the binnacle, red pole uppermost, and gradually raise it, until the needle was again horizontal. (88)

54. Any particular direction for the ship's head when using the vertical force instrument?

Not specially so, but E. or W. would be an advantage in order to get rid of the effect of fore and aft horizontal iron, should the ends of any such beams be near enough to affect the needle of the vertical force instrument (107) (fig. 66).

55. Must the compass be first corrected with the ship upright before touching the heeling error?

No ; in practice the heeling error is usually corrected first before the compass bowl is put into the binnacle.

56. How may the magnetic bearing of a distant object be found?

If the ship's position can be accurately plotted on the chart by sextant angles or other means, the magnetic bearing of the object in sight may be got from the chart. The mean of the compass bearings taken when the ship's head is steadied on eight equi-distant points, the cardinal and inter-cardinal usually, will also give the magnetic bearing.

57. If you had not time to make a complete swing, how may an approximate magnetic bearing be got?

The mean of two compass bearings of an object got when the ship's head is on any two opposite points, preferably E. and W., will give a good working bearing.

58. Why east and west?

Because heeling error is then least ; and if A and E exist and happen to be of the same sign, they tend to neutralise each other when heading E. and W.

59. When adjusting the compass by the bearing of a distant object, what precautions should be taken?

That the ship is far enough removed from the object to ensure that the radius of the circle, around the circumference of which the compass swings, does not materially affect the bearing of the distant object.

60. If you were compelled to swing for deviation, and no suitable object was sufficiently far distant for the purpose, what would you do?

Land a compass in a position free from local magnetic attraction,

with an observer in charge. Simultaneous bearings of the ship and shore compasses from each other are taken when the ship swings round. The shore bearings reversed will be the magnetic bearings of the shore compass from the ship, and the difference between the two sets of bearings will give the deviation for the corresponding direction of the ship's head.

61. What special arrangement is made at some ports to facilitate the adjustment of ship's compasses?

At Liverpool and Cronstadt, numbers have been painted on the face of dock walls. These numbers when seen in transit with a given inshore mark (St. Martin's Church Spire) indicate its *true* bearing. The figures in Cronstadt harbour when in line with the Foundry chimney are also *true* bearings (fig. 60).

NOTE.—The figures at Liverpool were first painted in 1856, on the recommendation of the Liverpool Compass Committee, and were originally magnetic bearings. The Mersey Docks and Harbour Board had the numbers altered from magnetic to true in 1893, so the variation for the current year must now be applied in order to get the magnetic bearing.

62. Describe how the ship's head is steadied on a particular course by means of the pelorus.

Turn the bearing plate until the required direction is at the lubber point, then clamp the sight vanes to the known magnetic bearing of the distant object. Swing the ship's head until the vanes are directed towards the object. The ship's head is then in the required direction. (11)

63. It is desired to find the deviation for the course the ship is steering; how may this be done with the pelorus?

Clamp the sight vanes to the bearing plate at the known magnetic bearing of a distant object. The vanes and the plate being clamped to each other, they will rotate together, so turn the plate until the vanes are directed to the object. The lubber line of the pelorus will then indicate the magnetic direction of the ship's head, and the difference between this direction and the compass course will be the deviation.

64. How often should the deviation be checked at sea?

Every watch, and frequently whenever the course is altered.

65. How do you account for the small fluctuations in the deviation of a ship's compass after it has been compensated?

The compensation is made on the assumption that the magnetic

character of the ship is due to a simple combination of purely hard iron and purely soft iron, whereas she is built of a steel, which partakes of the character of both, with the result that the magnetic condition of the ship is unstable and may be anything between the theoretical limits as defined by the terms hard iron and soft iron. These departures from the ideal magnetic condition attributed to the two varieties of iron is assisted by the vibration of the engines, from repairs, or shocks from heavy seas, also by steering on the same course for a considerable time, changes of latitude, cargo and trim.

66. Assuming the curve on the Napier's diagram in this book to represent the deviations of an uncompensated compass, state the direction of the ship's head, approximately, whilst building.

The deviation arising from sub-permanent magnetism is least when the ship is heading in the same, or in the opposite direction to that of the building slip, therefore in this case she must have been heading about E. by S., or W. by N., when on the stocks.

But the curve shows westerly deviation on north, a co-efficient $-C$, the north point of the compass has been drawn to port, thus giving evidence that the blue sub-permanent pole is on that side. Now, the ship's head must have been westerly in order to generate a blue pole to port, therefore, of the two directions, she must have been heading about W. by N. whilst building. We might have argued in the same way from the westerly deviation on east, co-efficient $-B$, which indicates that the blue sub-permanent pole is in the after part of the ship, so her head must have been northerly in the building yard and again, of the two directions E. by S. and W. by N., she must have been heading W. by N. (58).

67. How would you test the efficiency of a standard compass before proceeding with its adjustment?

Examine the graduations of the card, also the cap and pivot. Deflect the card and observe if it always comes to rest indicating the same direction; that it maintains a horizontal position when rotating, and that the annular space between the edge of the card and the inner wall of the bowl is equal all round in order to test the centreing of the card, also check its period which should be about 33 seconds.

See that the lubber line is in the midship fore and aft line of the ship, that the gimbals are working smoothly and the bowl nicely

balanced, that there are no nails or lose iron of any kind in the binnacle, or in the vicinity of the compass ; test the spheres and the Flinders bar for retained magnetism, also the correcting magnets to make sure the polarity agrees with the red and blue paint, and that the receptacles to receive them are in accordance with the rules prescribed. The magnetic axis of the needles should be parallel to a line drawn through the N. and S. points of the card, but this is tested in the works by means of special apparatus. (93)

68. How is the Kelvin azimuth mirror tested and adjusted?

By taking the bearing of a distant object with the arrow up and arrow down. The two readings should agree ; if not, the prism is adjusted by means of its retaining screws until they do.

69. Describe tentative methods of compass adjustment. What should be guarded against before commencing?

The compass should first be tested as in question 67, and movable iron should be in its sea position. The magnetic bearing of the distant object should be accurately known, and the ship far enough away from it so that the bearing will not be materially affected when swinging.

In practice the order in which the separate adjustments are made depends upon the prevailing circumstances. At a deviascope in a class room the following order gives the best results :—

(1) Head N. magnetic, correct co-efficient *C* with athwartship magnet.
(2) Head E. magnetic, correct co-efficient *B*; 4° with Flinders bar and the rest with a fore and aft magnet.
(3) Head N.E., magnetic, correct co-efficient *D* with spheres.
(4) Head N. by compass, heel model and correct heeling error with the vertical magnet.

The order recommended in the Admiralty Manual is—

(1) Compute, or estimate, the value of *D* and correct it with the spheres as directed in Table IV., Appendix.
(2) Place Flinders bar to correct an estimated induced *B* as directed in Table VI., Appendix.
(3) Correct heeling error with vertical magnet by means of the vertical force instrument.
(4) Head N. or S. and correct *C*.
(5) Head E. or W. and correct *B*.

Another order which is quite good theoretically is—

(1) Correct an estimated *D* with the spheres.

(2) Head as in building yard (this eliminates the deviation due to sub-permanent magnetism) and correct the deviation, if any, with the Flinders bar.

(3) Correct heeling error with vertical magnet as determined by the vertical force instrument.

(4) Head N. or S. and correct *C*.

(5) Head E. or W. and correct *B*.

70. What are the advantages of a compensated compass?

(1) The deviation being small a mistake in its application, or in the amount estimated, may not be very serious.

(2) The angle of swing of the ship's head as indicated by the compass is the same, or nearly so, as the arc of the horizon.

(3) The directive force of the needle is nearly equal on all headings and the card, in consequence, acts equally well on all courses.

(4) The compass when compensated for heeling error is steadier when the ship rolls.

71. What would be the effect on the compass if the spheres were attached to the bowl instead of the binnacle?

So long as the ship remained upright the spheres would act just as effectively if attached to the bowl instead of the binnacle, provided they were not so close as to become magnetised by induction from the needles. The binnacle, however, always stands perpendicular to the beam and the line joining the centres of the spheres is always parallel to the transverse beam no matter how much the ship may roll, so the beam and spheres maintain the same position relatively to each other always when the spheres are attached to the binnacle.

But the bowl being weighted and slung in gimbals, remains in the same horizontal plane and so changes its position relatively to the beams. If the spheres were attached to the bowl the line joining their centres would be horizontal always and, when the ship rolled, this line would be oblique to the line of the beams, the relative positions of the beam and spheres would change with every angle of heel and the spheres would correct neither the heeling error nor the quadrantal deviation.

72. How may the coefficients be computed from the deviation curve of an untouched compass?

Coefficient A is the mean of the deviations on N., S., E. and W.

Coefficient B is the mean of the deviations on E. and W. with the name changed on west.

Coefficient C is the mean on N. and S. with the name changed on South.

Coefficient D is the mean on N.E., S.E., S.W. and N.W. with the name changed on S.E. and N.W.

Coefficient E is the mean on N., S., E. and W. with the name changed on East and West. (93)

73. Why is the name of the semi-circular deviation on some headings changed?

The deviation due to hard iron is semi-circular and disappears when the ship is heading in the same way, or in the opposite, to her head as in building yard; this is called the neutral direction. The deviation is westerly on courses in the semi-circle to the right of her head when building and easterly when in the left hand semi-circle.

The sign of the deviation changes because the ship's poles revolve round the compass when swinging ship, the blue pole drawing the needle to the right hand during half the swing and to the left hand during the other half, the maximum deviation being reached when heading 90° away from the neutral point.

The total force from hard iron is resolved into two components, $+P$ to the bow, $-P$ to the stern, $+Q$ to starboard, $-Q$ to port, the coefficients B and C being the effect of those components on the compass.

74. A ship's head was S.W. when being built, what would be the signs of her sub-permanent coefficients?

Her head being S.W., the blue sub-permanent pole, that is South magnetic, would be four points on her port bow towards which the needle would be attracted giving a $+B$ and a $-C$.

75. A compass is surrounded by a wall of iron, a turret for example, what would you expect to find?

A very weak, if not useless, needle, owing to the lines of force flowing through the plating which forms an iron ring round the compass thus placing the needle within a circular magnetic field. (74)

76. What is meant by 12 inches of Flinders bar? And what effect has Flinders bar on the heeling error?

The top end of the bar in a standard compass is always kept about $\frac{1}{12}$ of its length above the level of the needles, its total length

in the brass container is always 24 inches being made up of convenient pieces of soft iron and wood, so that 12 inches of Flinders bar means 12 inches of the soft iron rod resting on 12 inches of wood.

When the ship heels the lower end of the bar swings to windward of the vertical plane passing through the needle; in the north hemisphere the lower end being red repels the needle to low side of the ship. (109) Page 110

77. Suppose the sub-permanent blue pole produced the same amount of heeling error as a vertical iron rod below the level of the compass, trace the changes in the heeling error you would expect to find when the ship sailed from N. to the S. hemispheres.

In the N. hemisphere the heeling error would be due to the combined action of both forces and would therefore be large, and to the high side. On proceeding towards the equator the effect of the vertical iron would get less, and on the equator it would have no effect, the error then being due to the sub-permanent blue magnetism only but still to the high side. On crossing the equator, the top end of the vertical iron would change from blue to red, increasing in strength as the ship penetrated into the southern hemisphere, until, eventually, the red induced pole would become equal to the blue sub-permanent pole, and no heeling error would appear, as these two forces would now be equal and opposite. On going further south the red pole in the vertical iron would dominate the position and repel the needle to the low side of the ship. (91)

78. The top end of a derrick post on the starboard side and abaft the compass is close enough to affect the needle. What kind of deviation will it produce? Name the co-efficients with their signs, and describe how this force may be compensated?

A semi-circular deviation. Co-efficients $-B$ and $+C$. The effect of the force may be counteracted by placing a Flinders bar on the opposite side of the compass, or two pieces of Flinders bar, one placed on the fore side of the binnacle and the other on the port side of the binnacle. The difficulty, in practice, would be to determine just how much deviation to compensate with these correctors. (63)

79. How may a co-efficient *A* be demonstrated on the deviascope by means of soft iron?

By placing two rods in the horizontal plane in the form of a T so that the compass is in one of the corners. (78)

80. Why is it just as desirable to compensate heeling error in steamers as it is in sailing ships?

Because the force causing heeling error acts first to one side then to the other with every roll of the ship, the result being a very unsteady compass, especially in high latitudes. (92) Page 85

81. What is the heeling error constant?

This is a constant, peculiar to each compass, which represents the diminution of the directive force of the needle and the corresponding effect this would have on the horizontality of the vertical force instrument when measuring the effect of the vertical force in the ship which produces the error when she heels.

Heeling error constant $=\lambda\ (1-d)$ where $\lambda=$say .9, and d is the natural sine of co-efficient D.

The scale reading when horizontalised on shore multiplied by the constant gives a modified reading to which the sliding weight should be set before adjusting for the heeling error with the vertical magnet. When the value of this multiplier is not known the adjuster places the vertical correcting magnet in a position so that the north end of the vertical force instrument points slightly upwards. (107)

82. How would heeling error be affected in the following cases?

(*a*) Heading in the same direction and changing tacks.

(*b*) Course changed from N. to S. and tack changed.

(*c*) Change of geographical position.

In (*a*) The error would change its name.

In (*b*) Retain the same name.

In (*c*) It would decrease in amount when the ship approached the equator, would probably continue to decrease on crossing the equator and might then vanish altogether, afterwards reappearing with a changed name. (92)

83. A vessel is swung and adjusted with a list, what effect would this have on the co-efficients *A*, *B*, *C*, *D*, and *E*, when upright?

No effect on A; nor on B because heeling error vanishes when ship's head is east; but it would increase or decrease the value of C as the heeling error is greatest when heading north. The spheres correct the quadrantal deviation as well as the heeling error due to a transverse beam and if these are properly placed co-eff. D will not be affected; E is always small and the heeling error, if any, due to diagonal beams is negligible.

84. Given $+A=2°$ and $+E=2°$. What is the result when these two co-efficients are combined?

When A and E are of equal value they produce, in combination, a semi-circular deviation which does not change its name. If they are of the same sign the maximum value is on N and S. decreasing to zero on E. and W., but when the signs differ the maximum value appears on E. and W.

Head.	+A.	+E.	Dev.	Head.	+A.	−E.	Dev.
N.	+2	+2	+4	N.	+2	−2	0
E.	+2	−2	0	E.	+2	+2	+4
S.	+2	+2	+4	S.	+2	−2	0
W.	+2	−2	0	W.	+2	+2	+4

85. Describe how the relative directive force of the needle is found?

The time taken by a needle to make a certain number of horizontal vibrations on shore in a place quite free from local magnetic attractions is observed. The time taken by the same needle to make the same number of vibrations when placed in the compass bowl is also observed. The shore time squared divided by the ship time squared gives the value of the directive force on board relatively to that on shore for the direction of ship's head only. The force on shore is taken as unity.

86. Define co-efficient Lambda. How is it found?

Lambda is the ratio the mean horizontal force of the compass on board bears to its horizontal directive force on shore. The value of Lambda is found experimentally by vibrating a needle in the compass bowl with her head on equi-distant courses. The directive force on each heading has to be multiplied by the cosine of the deviation for that head and the mean of these results gives Lambda. Its value is about .9 at a well placed standard compass. (105) (106)

87. Explain why the mean directive force of the needle is weakened on board ship.

The forces producing semi-circular deviation, namely, subpermanent magnetism and vertical induction, increase the directive

force during half the swing and decrease it equally on the other half swing the mean result being unity, the same as on shore. But the continuous transverse beam producing $+D$ diminishes the power of the needle on all headings, because the induced red pole in the north end of the beam is interposed between the needle and the blue pole of the earth, the latter being the magnetic power provided by Nature to direct a needle. (74) Fig. 44.

88. Apart from calculations, is a knowledge of Lambda of any practical value?

Yes, particularly when selecting a position for the compass, especially in fighting ships where it is impossible to keep it at a reasonably safe distance from heavy masses of unsymmetrically arranged and moveable iron. Other things being equally convenient the best position for the compass, so far as directive force is concerned, is where Lambda is greatest. (106)

89. What is the principle underlying the operation of adjusting a compass with the aid of a deflector? Describe the method of using the Kelvin deflector.

The assumption is that if the directive force of the needle is the same on all headings there shall be no deviation.

The operation of adjusting is as follows:—First, induced B and co-efficient D are estimated and corrected, also the heeling error, leaving only the deviation due to sub-permanent magnetism to correct, that is co-efficients B and C. The instrument is used when distant objects are obscured: the vessel is invariably under way and her head is kept steady in the required directions by the steering compass.

(1) Head N. by compass. Place deflector on the centre of the bowl. Open out the legs and deflect the card to a normal deflection of 90°, the pointer of the instrument lying over the E. by N. point of the card. Note the scale reading (say 10) and lift off deflector.

(2) Head S. by compass. Place deflector on centre of bowl. Open out legs, and deflect the card 90°. Note the scale reading (say 14°). Now set the scale reading to the mean of the two readings, namely 12, and, without lifting off the deflector, introduce fore and aft magnets into the binnacle until the card regains the normal deflection of 90° when the pointer of the instrument is exactly above the E. by N. point of the card.

(3) Head E. by compass. Deflect the card 90°, and note the scale reading necessary to do so (say 8).

(4) Head W. by compass. Deflect the card 90°, and note the scale reading, say 12. Now, set the scale reading at the mean reading, namely 10, and, without lifting off the deflector, insert athwartship magnets in the binnacle until the card is deflected 90°.

(5) The mean of the two mean readings, namely 12 and 10 is 11, so, with ship's head still on west, set the scale reading to 11 and move the spheres out a bit until the card settles at the normal deflection of 90°. The directive force of the compass is now equalised on all courses. (102)

90. What is a solenoid?

A solenoid is a helix, or spiral, of copper wire the ends of which are attached to the terminals of a battery. It acts in the same way as a magnet. A blue pole appears at the end in which the current circulates right-handed when looked at end on. If the ends of the wire are bent back into the cavity of the helix and brought out about its middle as shown in fig. 69, and the whole system suspended by a fine thread so as to rotate freely on a central vertical axis, the solenoid would set itself in the magnetic meridian the end to the right hand being directed to the north.

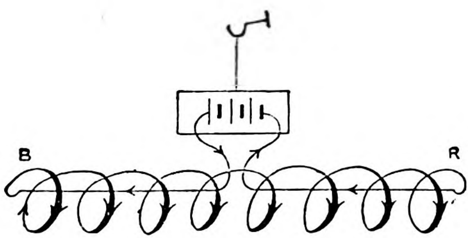


FIG. 69.—A SOLENOID.

NOTE.—A simple voltaic cell consists of two plates, one zinc the other copper, placed in a weak solution of sulphuric acid (fig. 70). An electrical current is thus generated which flows from the active to the passive plate. In this case the copper plate is unaffected by the acid and is said to be passive, but the zinc plate is said to be active because it is dissolved by the resulting chemical action. A number of such cells when connected forms a battery and it is usual to illustrate a battery by means of a few thin and thick lines |ı|ı|ı, the thin

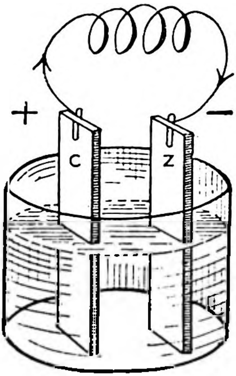
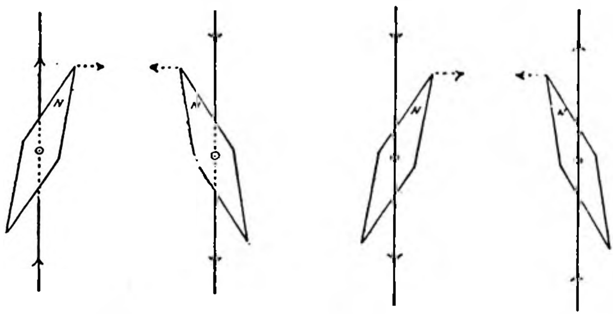


FIG. 70.—A SIMPLE VOLTAIC CELL.

lines to represent the copper plate which is positive and the thick lines the zinc, or negative plate. The current flows from positive to negative through the external wire.

91. Describe how an electric current affects (*a*) a needle, (*b*) a soft iron bar placed in the cavity of a helix.

(*a*) Ampere's Rule :—Suppose the observer to be swimming in the wire in the same direction as the current, and with his face



Needle and hand above the wire. Needle and hand below the wire.

FIG. 71.

towards the needle, the north seeking pole of the needle is deflected towards his left hand.

The "Rule of Thumb" seems to meet all the requirements of compass work. Imagine the needle to be held in the palm of the *right* hand, its north end being in the direction of the four fingers. Imagine the back of the hand to be in contact with the wire and the fingers pointing in the direction the current is flowing, the thumb will then indicate the direction to which the north end of the needle will turn.

(*b*) If a soft iron rod is placed in the cavity of a helix it will become magnetised when a current is switched on, the blue pole appearing at the end having the right-handed circulation. The iron rod when inserted into the helix converts the solenoid into a "straight" electro magnet.

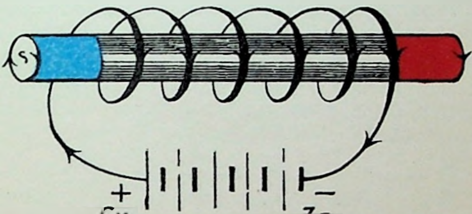


FIG 72.—A STRAIGHT ELECTRO MAGNET.

A current when passing along a wire creates a local atmosphere, or flux, which rotates clockwise around the wire when looking end on

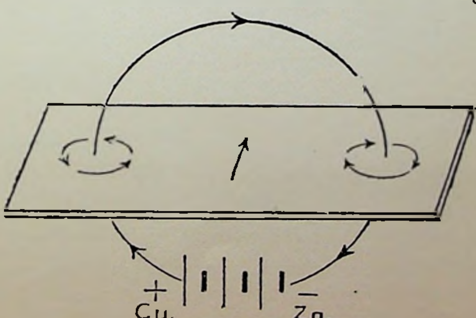


FIG. 73.—EFFECT OF AN ELECTRIC CURRENT ON IRON FILINGS.

to the wire in the direction in which the current flows. In fig. 73 a circular wire is passed through a piece of cardboard, the ends of the wire being in contact with a battery and a current switched on. Iron filings when sprinkled on the paper arrange themselves in a circular field around the wire. When a needle is brought close to the wire its north end will turn in the direction of the arrows, thus establishing the presence of a rotary flux.

92. Describe the construction and the properties of an electro magnet.

A "horse shoe" electro magnet is formed by two soft iron cores resting on a soft iron base. A coil of insulated copper wire is wound round the core pieces the ends being attached to the positive and negative poles of a battery, or to the terminals of an electric circuit. During the passage of the current the cores are powerfully

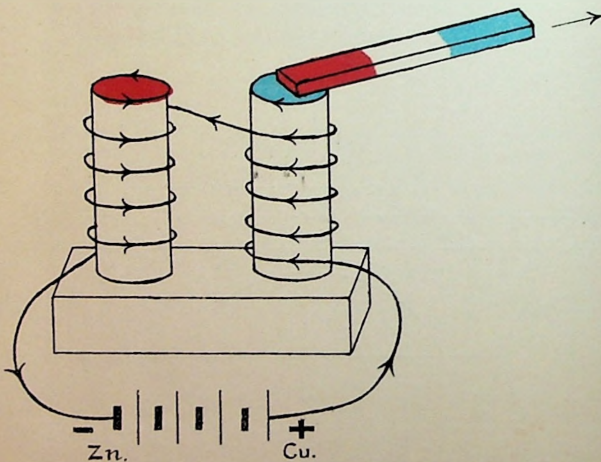


FIG. 74.—A "HORSE SHOE" ELECTRO MAGNET.

magnetised. The blue, or south, or positive pole (these are different ways of naming the same thing) appears in the core in which the current circulates clockwise when looked at end on. The strength of an electro magnet depends on the mass of soft iron, the number of

turns in the coil and the power of the electric current. The weaker types are used in telegraphy, telephony, ringing bells, etc., and the more powerful types are used for lifting plates and iron fittings in shipyards, discharging scrap iron cargoes. The Board of Trade issued a Notice to Mariners in 1922 calling the attention of masters to the powerful effect produced on the permanent magnetism of the ship by the loading and discharging of cargo by means of electro-magnets. Cases have recently occurred where the permanent magnetism of a vessel has been so altered as to render the compass unreliable, and as a large amount of the induced magnetism may be subsequently shaken out, adjustment of the compass after loading or discharging by this method is of very little value. Masters are consequently warned that no reliance can be placed on the correct adjustment of their compasses after electro-magnets have been used for loading or discharging. If electro-magnets are used every precaution should be taken and the ship should be swung for deviations before proceeding to sea, the deviations being checked at every subsequent opportunity.

The compass card should be unshipped during loading and discharging by this method, as the constant swinging is likely to blunt the pivot or damage the sapphire cap.

93. How is a bar of iron or steel magnetised?

Iron is magnetised temporarily by the earth, a red pole appearing in the end pointing northwards. It is magnetised more durably by contact with another magnet (par. 19), but more strongly and durably still by drawing the steel bar from one end to the other across one pole of an electro-magnet, and then drawing it in the opposite direction across the other pole (fig. 74). The end of the bar which is the last to leave the blue, that is the south or positive pole of the electro-magnet, acquires red, or north seeking, polarity.

94. Could quadrantal deviation be compensated by means of one corrector only?

Yes, but the single sphere would have to be equal in magnetic strength to the two spheres universally employed. This would probably mean a very large corrector as magnetism is mainly confined to the surface of iron only; then there would be a lack of balance and symmetry and, unless the deviation was very small, there is the possibility that a single corrector might be too big and unwieldy.

95. Why are compass bowls made of brass or copper?

A magnetic needle comes to rest sooner when oscillating within a bowl made of brass or copper than in one made of wood, and a copper bowl is found to be the most effective in damping the motion of the needle. When the ship's head is swinging in azimuth the mechanical movement between the needle and the metal bowl generates electro-magnetic induction, the induced current being in such a direction that it tends to bring the needle to rest. This is known as Lenz's Law, hence the reason why the bowl is made of brass or copper because the compass is steadier than in bowls made of other material.

96. What precautions should be taken when adjusting the compass in a ship fitted with electric lighting and wireless?

Switch binnacle lights on and off and start up the wireless plant to make sure that there is no leakage of current to affect the compass.

97. State generally the difference between magnetism and electricity.

The flux, or atmosphere, surrounding a magnet remains the same, its intensity is unimpaired and does not vanish when the magnet is handled. The magnet is charged permanently. But a flow of electricity from a charged body is accompanied by a disappearance of lines of force.

Magnetic attraction is confined to one or more substances, iron principally. Electrical attraction is felt by all substances.

Electricity, although not a fluid, may be conducted along certain bodies just as a current of water flows, but this is not possible with magnetism.

Positive electricity flows from a conductor of higher potential to a conductor of lower potential, and this electric current creates a magnetic action in its near neighbourhood which can be detected by a magnet or galvanometer, thus, only when electricity moves does it produce magnetic action. If the ends of a spiral of insulated copper wire are attached to a galvanometer and a magnet is placed inside the spiral coil, nothing happens, but if the magnet is pulled out of the coil the needle of the galvanometer at once moves, thus, or when the magnet is moved under certain conditions, does it pr an electric action.

98. Describe how a combination of *D* and *E* may be corrected with a pair of spheres.

The spheres would need to be placed slightly out of the athwartship line depending on the relative values of D and E. This would only be resorted to if E were of appreciable value, say over 1°.

The Angle of Obliquity.

E varies as 2 Cos co, and D varies as 2 Sin co .

$$\therefore \frac{E}{D} = \frac{2 \text{ Cos co}}{2 \text{ Sin co}} = \text{Cot co} = \text{tan twice the angle}$$

from the athwartship line for placing the spheres—call this angle θ.

For example, if $+D$ were 4° and $-E$ were 1·5°, then $\tan 2\theta = \frac{E}{D} = \frac{1{\cdot}5}{4} = {\cdot}375$, $\therefore 2\theta = 20°$ and $\theta =$ 10°, the angle to which the globes should be placed out of the athwartship line, starboard globe forward to correct $-E$, see figure, No. 4, page 68.

The Distance to Place Spheres.

The maximum quadrantal deviation is

$$X° = \sqrt{D^2+E^2} = \sqrt{4^2+1{\cdot}5^2} = 4{\cdot}27°.$$

On referring to Table IV, Appendix, it would require a pair of 7-inch spheres placed 1·5+ 8·5=10 inches away from the compass, centre to centre and 10° out of line to correct the 10″ card of a standard compass.

99. If $+D$ = 2°, and $+E$ = 2°, how should a pair of spheres be placed to correct both coefficients?

The line joining the spheres should be 22½° out of the athwartship line, port sphere forward.

100. If the lubber line is misplaced 2° to port, how would this affect the deviation on all courses?

The lubber line being too much to the left, all compass courses steered would also be too much to the left of the corresponding magnetic courses thus producing a constant 2° East deviation, $+A$

CHAPTER IX.

112. In previous lectures we have confined ourselves to a general description of the cause and effect of deviation and its compensation. But a knowledge of the mathematical side of the subject is also desirable, as it then becomes possible to resolve the ship's total magnetic force into its several constituents, and to trace the probable changes that may be expected in the compass deviation as the ship changes her magnetic latitude.

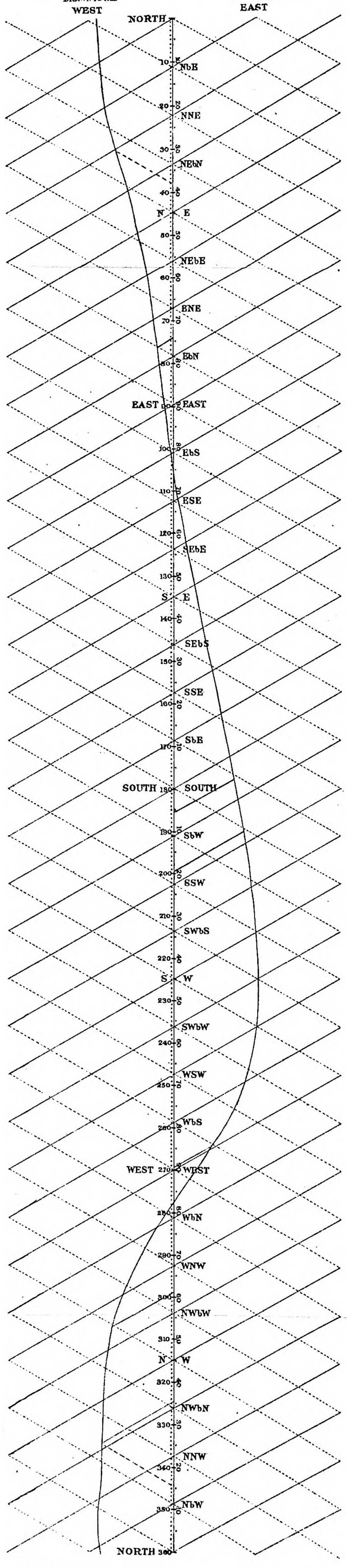
A few of the calculations are included in the Board of Trade examination on compass deviation, and they also form part of the work required for an extra master's certificate. In practical navigation, however, compass work is usually confined to working up azimuths at sea, in order to determine the correct deviation for setting the course and checking the deviation table. It is the invariable practice to keep a record in a deviation log book of the observations made to determine the error of the compass, as a guide for subsequent voyages when in the same locality. There are various forms, the most common being to have a few pages of a book for each point of the compass, the pages being columned off and headed for date, time, position, variation, true bearing and name of object, compass bearing of object, error, deviation, heel, remarks.

113. The Napier Diagram provides a graphical method of depicting the bold deviations of an uncompensated compass, but it is of little value when the deviations are small, as they should be, in a well adjusted compass. The special advantage of the Napier diagram lies in the facility it offers of making a complete table of deviations from observations made on a few irregular points round the compass, and of converting compass courses into magnetic courses and the reverse.

The central line represents the rim of a compass card, cut and straightened out, the degrees of which form the scale of measurement. Diagonal lines intersect this central line at an angle of 60°, dotted lines being drawn downwards from left to right and plain lines downwards from right to left. East deviations are laid off to the right of the central line and west deviations to the left of it, care being taken

To accompany Example I. Chap. IX.

DIAGRAM



Ships Name .... Place .... Latitude .... Longitude .... Date ....

to measure the deviation for the respective points along the dotted line when it is given for a compass course, and along the plain line when it is given for a magnetic course.

EXAMPLE I.

1. Having taken the following equi-distant compass bearings of a distant object, find the magnetic bearing of the object, thence the deviations, and plot them on a Napier's diagram.

Ship's Head by Standard Compass.	Bearing of Distant Object by Standard Compass.	Magnetic Bearing of Distant Object.	Deviation for Ship's Head.
N.	N. 38° W.	N. 60° W.	22° W.
N.E.	N. 50° W.	,,	10° W.
E.	N. 57° W.	,,	3° W.
S.E.	N. 67° W.	,,	7° E.
S.	N. 79° W.	,,	19° E.
S.W.	N. 83° W.	,,	23° E.
W.	N. 63° W.	,,	3° E.
N.W.	N. 43° W.	,,	17° W.
	8)480		
magnetic bearing =	N. 60 W.		

114. To plot the Curve.—Lay off the deviations along the dotted line, measuring the several values from their respective points on the central line. For example, 22° W. deviation is measured upwards on the dotted line from N., 10° W. deviation on the dotted line from N.E., 3° W. deviation from E., and 7° E. deviation downwards from S.E. and so on.

Through these spots draw a fair curve. The length of the dotted line, or a line parallel to it, intercepted between the central line and the curve, will be the deviation on the intermediate compass courses, while the intercepted length of the plain line will be the deviation on the magnetic courses expressed in degrees of the scale.

EXAMPLE II.

Given the following magnetic courses, find the corresponding compass courses from the foregoing curve :—

Magnetic courses—N.N.E. S.E. S. ½ W. N.W. by W. ½ W.

Compass courses—N. 37° E. S. 50° E. S. 11° E. N. 45° W.

Proceed as follows when converting a magnetic course into its corresponding compass course :—From the magnetic point on the central line move out to the curve along, or parallel to, a plain line, and then return from the curve along, or parallel to, a dotted line. The

intersection of the dotted line with the central line gives the corresponding compass course.

> "If you wish to steer the course allotted
> Depart by plain and return by dotted."

Example III.

Given the following compass courses, find the corresponding magnetic courses:—

Compass courses—E. by N. South W. by S. N. by W. ½ W.
Magnetic courses—N. 74° E. S. 19° W. S. 89° W. N. 36° W.

In this case, the compass courses are given, so move out from the central line to the curve along a dotted line, and return on, or parallel to, a plain line, when the intersection of the plain and mesial lines will give the magnetic course.

> "From compass course, magnetic course to gain
> Depart by dotted and return by plain."

Example IV.

Given ship's head by compass, S.S.W., find the deviation, and then convert the following compass bearings into magnetic bearings:—

Compass bearings—N. 47° E. S. 30° E. S. 5° E. N. 10° W
Magnetic bearings—N. 69° E. S. 8° E. S. 17° W. N. 12° E.

The length of the dotted line intercepted between S.S.W. and the curve is the deviation for the ship's head. It measures 22° E., and is named east, because the curve lies to the right of the central line. Apply this deviation to each of the compass bearings, to the right hand when it is named east, but to the left hand when it is named west.

Exercise I.

1. From the following compass bearings find the magnetic bearing of the distant object, thence the deviations, and then plot them on a Napier's diagram.

Ship's Head by Compass.	Bearing of Distant Object by Compass.	Deviation Required.	Ship's Head by Compass.	Bearing of Distant Object by Compass.	Deviation Required.
N.	N. 42° W.		S.	N. 48° W.	
N.E.	N. 62° W.		S.W.	N. 35° W.	
E.	N. 65° W.		W.	N. 24° W.	
S.E.	N. 60° W.		N.W.	N. 24° W.	

2. With the deviation as above give the courses you would steer by the standard compass to make the following magnetic courses :—

Magnetic courses—N.N.E. E.S.E. W.S.W. N.W.
Compass courses—

3. Having steered the following courses by the compass, find the correct magnetic courses from the foregoing deviation curve :—

Compass courses—N.E. by N. E. by S. W.S.W. N.N.W.
Magnetic courses—

4. You have taken the following bearings of distant objects by the standard compass, with the ship's head S.W. by W., find the magnetic bearings.

Compass bearings—N. by E. S.W. by W. S.E. N.W. by N.
Magnetic bearings—

EXERCISE II.

1. Plot a curve of deviations on a Napier's diagram from the following information :—

Ship's Head by Compass.	Bearing of Distant Object by Compass.	Deviation Required.	Ship's Head by Compass.	Bearing of Distant Object by Compass.	Deviation Required.
N.	S. 89° W.		S.	S. 88° W.	
N.E.	S. 80° W.		S.W.	N. 78° W.	
E.	S. 70° W.		W.	N. 68° W.	
S.E.	S. 76° W.		N.W.	N. 77° W.	

NOTE.—Re-name the last three bearings from south, add up, and take the mean as before to get the magnetic bearing.

2. Using the same curve, convert the following magnetic courses into their corresponding compass courses.

Magnetic courses—E. by N. E. by S. W. ½ S. N.W.
Compass courses—

3. Turn the following compass courses into magnetic courses:—

Compass courses—E. ½ N. S.E. by E. S. ½ W. W. by N. ½ N.
Magnetic courses—

4. When the ship's head was W. by N. ½ N. by compass, the bearings of several distant objects were taken, convert them into magnetic bearings.

Compass bearings—N. 30° E. N. 76° W. S. 56° W. S 80° E.
Magnetic bearings—

Exercise III.

1. The ship was swung for deviation as follows:—Find the magnetic bearing of the distant object and run in a curve of the deviations on a Napier's diagram.

Ship's Head by Compass.	Bearing of Distant Object by Compass.	Deviation Required.	Ship's Head by Compass.	Bearing of Distant Object of Compass.	Deviation Required.
N.	N. 8° E.		S.	N. 8° E.	
N.E.	N. 3° W.		S.W.	N. 25° E.	
E.	N. 15° W.		W.	N. 37° E.	
S.E.	N. 4° W.		N.W.	N. 24° E.	

Note.—Add together the easterly bearings, then the westerly bearings, subtract the less from the greater, and divide the result by eight in order to get the mean or magnetic bearing.

2. From the same curve, convert the following magnetic courses into compass courses :—

Magnetic courses—E. ½ N. E. ½ S. S. ½ W. N. ½ W.
Compass courses—

3. Using the same curve, turn the following compass courses into magnetic courses :—

Compass courses—N. ½ E. S. ½ E. S.S.W. W.N.W.
Magnetic courses—

4. Several distant objects bore by compass as follows, when the ship was heading E. by N. ½ N., find their magnetic bearings:—

Compass bearings—N. 60° E. S. 35° E. S. 70° W. N. 10° W.
Magnetic bearings—

ANSWERS.

Exercise I.

1. Magnetic bearing—N. 45° W. Deviations—3° W. 17° E. 20° E., 15° E. 3° E. 10° W. 21° W. 21° W.

2. Compass courses—N. 19° E. S. 86° E. S. 88° W. N. 28° W.

3. Magnetic courses—N. 47° E. S. 58° E. S. 52° W. N. 37° W.

4. Deviation for ship's head—13° W. Magnetic bearings, N. 2° W., S. 43° W., S. 58° E., N. 47° W.

Exercise II.

1. Magnetic bearing—W. Deviations—1° E., 10° E. 20° E. 14° E. 2° E. 12° W. 22° W. 13° W.
2. Compass courses—N. 64° E. N. 82° E. N. 75° W. N. 35° W
3. Magnetic courses—S. 76° E. S. 39° E. S. 5° W. S. 87° W.
4. Deviation for ship's head—20° W Magnetic bearings—N. 10° E. S. 84° W. S. 36° W. N. 80° E.

Exercise III.

1. Magnetic bearing—N. 10° E. Deviations—2° E. 13° E. 25° E. 14° E. 2° E. 15° W. 27° W. 14° W.
2. Compass courses—N. 64° E. N. 74° E. S. 5° W. N. 5° W.
3. Magnetic courses—N. 8° E. S. 3° E. S. 16° W. N. 89° W.
4. Deviation for ship's head 22° E—Magnetic bearings—N. 82° E. S. 13° E. N. 88° W. N. 12° E.

115. The Co-efficients by Calculation.—An approximate value of the co-efficients may be got from the deviations found on the cardinal and inter-cardinal points, by paying attention to the following precepts :—

A plus sign represents *E* deviation (+).
A minus sign represents *W* deviation (−).
An attraction to the bow is +, to the stern −.
An attraction to the starboard side +, to the port side −.

Example V.

Calculate the co-efficients *A*, *B*, *C*, *D*, and *E* from the deviations given in Example I.

Co-efficient A is the mean value of the deviations on the cardinal points.

Head	N.	Dev.	−22°
,,	S.	,,	+19
,,	E.	,,	−3
,,	W.	,,	+3
			−25
			+22
		4)	−3
		A =	−0°45′

Co-efficient B is the mean value of the deviations on E. and W., with the sign at W. reversed.

$$\begin{array}{lll} \text{Head E. Dev.} = & -3^\circ & \\ \text{,, W. ,,} = & -\underline{3} & \text{(sign reversed)} \\ & 2)\underline{6} & \\ B = & -\underline{\underline{3^\circ}} & \end{array}$$

Co-efficient *C* is the mean value of the deviations on N. and S., with the sign at S. reversed.

$$\begin{array}{lll} \text{Head N. Dev.} = & -22^\circ & \\ \text{,, S. ,,} = & -\underline{19} & \text{(sign reversed)} \\ & 2)\underline{41} & \\ C = & -\underline{\underline{20^\circ 30'}} & \end{array}$$

Co-efficient *D* is the mean value of the deviations on N.E., S.E., S.W., and N.W., with the signs reversed at S.E. and N.W.

$$\begin{array}{lll} \text{Head N.E. Dev.} = & -10^\circ & \\ \text{,, S.W. ,,} = & +23 & \\ \text{,, S.E. ,,} = & -\ 7 & \text{(sign reversed)} \\ \text{,, N.W. ,,} = & +\underline{17} & \text{(,, ,,)} \\ & +40 & \\ & -\underline{17} & \\ & 4)\underline{23} & \\ D = & +\underline{\underline{5^\circ 45'}} & \end{array}$$

Co-efficient E is the mean value of the deviations on N., S., E. and W., with the signs reversed at E. and W.

$$\begin{array}{lll} \text{Head N. Dev.} = & -22^\circ & \\ \text{,, S. ,,} = & +19 & \\ \text{,, E. ,,} = & +\ 3 & \text{(sign reversed)} \\ \text{,, W. ,,} = & -\ \underline{3} & \text{(,, ,,)} \\ & -25 & \\ & +\underline{22} & \\ & 4)\underline{\ 3} & \\ E = & -\underline{\underline{0^\circ 45'}} & \end{array}$$

Answers.—$A = -0^\circ\ 45'$. $B = -3^\circ\ 0'$. $C = -20^\circ\ 30'$. $D = +5^\circ\ 45'$. $E = -0^\circ\ 45'$.

Given the following deviations, with ship's head by compass, calculate the values of A, B, C, D, and E.

EXERCISES.

1. N. = 7° W. N.E. = 13° W. E. = 22° W. S.E. = 23° W. S. = 6° E. S.W. = 29° E. W. = 19° E. N.W. = 3° E.

2. N. = 3° E. N.E. = 21° E. E. = 20° E. S.E. = 10° E. S. = 2° W. S.W. = 14° W. W. = 21° W. N.W. = 17° W.

ANSWERS.

1.—$A = -1^\circ$. $B = -20^\circ\ 30'$. $C = -6^\circ\ 30'$. $D = +9^\circ$. $E = +0^\circ\ 30'$.

2. —$A = 0^\circ$. $B = +20^\circ\ 30'$. $C = +2^\circ\ 30'$. $D = +3^\circ\ 30'$. $E = +0^\circ\ 30'$.

116. To construct a Table of Deviations.—The approximate deviations can be found by means of the following formula, provided the deviation does not exceed 20° or thereby.

Dev.$=A + B$ Sin. Co. $+ C$ Cos. Co. $+ D$ Sin. 2 Co. + Cos. 2 Co., where Co. represents the direction of the ship's head.

A complete table of deviations may be calculated when this formula is applied to each of the 32 points of the compass in succession, but the process is too tedious to be used in practical compass work, nevertheless the working of an example or two is a very fine exercise in mastering the signs and effects of the coefficients.

Given $-A=0^\circ\ 45'$, $-B=3^\circ$, $-C=20^\circ\ 30'$, $+D=5^\circ\ 45'$, $-E=0^\circ\ 45'$; calculate the deviation on (1) N. 30° E., (2) S. 65° E., (3) S. 14° W., (4) N. 55° W.

(1) Dev.$=A+B$ Sin. Co.$+C$ Cos. Co.$+D$ Sin. 2 Co.$+E$ Cos. 2 Co.

Dev. $= A + B$ Sin. Co. $+ C$ Cos. Co. $+ D$ Sin. 2 Co. $+ E$. Cos. 2 Cos.

(1) Dev. $= \cdot 75^\circ$ 3 Sin. 30°. 20·5 Cos. 30°. 5·75 Sin. 60°. ·75 Cos. 60°
$= \cdot 75^\circ$ $3 \times \cdot 50$. $20\cdot 5 \times \cdot 87$. $5\cdot 75 \times \cdot 87$. $\cdot 75 \times \cdot 50$.
Apply co-efficient signs for N. 30° E.
$= -\cdot 75 - 1\cdot 50 - 17\cdot 83 + 5\cdot 00 - \cdot 37$.
$= -20\cdot 45 + 5\cdot 00 = -15\cdot 45$.
Dev. on N. 30° E. is 15·45° W.

(2) Dev. $= \cdot 75$. 3 Sin. 65°. 20·5 Cos. 65°. 5·75 Sin. 130°. ·75 Cos. 130°
$= \cdot 75$. $3 \times \cdot 91$ $20\cdot 5 \times \cdot 42$. $5\cdot 75 \times \cdot 77$. $\cdot 75 \times 64$.
Apply signs for S. 65° E.
$= -\cdot 75 - 2\cdot 73 + 8\cdot 61 - 4\cdot 43 + \cdot 48$.
$= +9\cdot 09 - 7\cdot 91 = +1\cdot 18$.
Dev. on S. 65° E. is 1·18° E.

(3) Dev. $= \cdot 75$. 3 Sin. 14°. 20·5 Cos. 14°. 5·75 Sin ·28°. ·75 Cos. 28°.
$= \cdot 75$. $3 \times \cdot 24$. $20\cdot 5 \times \cdot 97$. $5\cdot 75 \times \cdot 47$. $\cdot 75 \times \cdot 88$.
Apply signs for S. 14° W.
$= -\cdot 75 + \cdot 72 + 19\cdot 90 + 2\cdot 70 - \cdot 66$
$= +23\cdot 32 - 1\cdot 41 = +21\cdot 91$.
Dev. on S. 14° W. is 21·91° E.

(4) Dev. $= \cdot 75$. 3 Sin. 55°. 20·5 Cos. 55°. 5·75 Sin. 110°. ·75 Cos. 110°
$= \cdot 75$. $3 \times \cdot 82$ $20\cdot 5 \times \cdot 57$. $5\cdot 75 \times \cdot 94$. $\cdot 75 \times \cdot 34$.
Apply signs for N. 55° W.
$= -\cdot 75 + 2\cdot 46 - 11\cdot 68 - 5\cdot 40 + \cdot 25$.
$= -17\cdot 83 + 2\cdot 71 = -15\cdot 12^\circ$.
Dev. on N. 55° W. is 15·12 W.

117. The part of the equation B sin. co. + C cos. co. expresses the semi-circular deviation, and referring to fig. 75 it may be explained that, if $O\,E$ represents the maximum value of B when heading E., then $L\,M$ will represent its value when heading N.N.E.

In triangle $L\,O\,M$:— $O\,M = O\,E =$ co.eff. $B =$ dev. on E.
$L\,M =$ value of B on N.N.E.
Angle $L\,O\,M =$ N N E.
but $L\,M = O\,M$ sin $L\,O\,M$.
$\therefore$ value of B on N.N.E. $= B$ sin. N.N.E.
Again, if $O\,N = O\,M =$ Coeff. $C =$ Dev. on North.
then $O\,L =$ value of C on N.N.E.
$O\,L = O\,M$ Cos. $L\,O\,M = C$ Cos. $22\frac{1}{2}°$.

Similarly, if $O\ S$ represents the maximum value of C when heading S., then $O\ W$ represents its value on W.S.W.

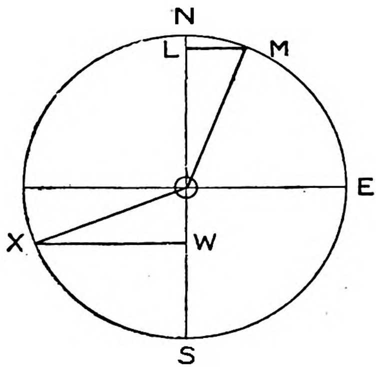


FIG. 75.

In triangle $O\ X\ W$.—$O\ X = O\ S$ = Co-eff. C = Dev. on S.

$O\ W$ = value of C on W.S.W.

Angle $W\ O\ X$ = W.S.W.

but $O\ W = O\ X \cos\ W\ O\ X$.

$\therefore$ value of C on W.S.W. = C Cos. W.S.W.

The expression D sin. 2 co. + E cos. 2 co. represents the quadrantal deviation.

In fig. 76, if $X\ W$ represents the maximum value of D when heading N.E., then $Z\ Y$ represents its value when heading N.N.E.

Now $\frac{Z\ Y}{X W} = \frac{\text{sin. } Z\ O\ Y}{\text{sin. } X\ O\ W} = \frac{\text{sin. 2 pts.}}{\text{sin. 4 pts.}}$, but the range from maximum to zero of the quadrantal deviation takes place in a swing of 45°, instead of 90°, so in order to utilise the ordinary mathematical tables, it is necessary to double the angles, thus $\frac{Z\ Y}{X W} = \frac{\text{sin. 2 pts.}}{\text{sin. 4 pts.}}$ becomes $\frac{Z\ Y}{X W} = \frac{\text{sin. 4 pts.}}{\text{sin. 8 pts.}} = \frac{\text{sin. 4 pts.}}{1}$ because sin. $90° = 1$ $\therefore$ $Z\ Y = X\ W$ sin. 4 pts., that is to say, the value of D on N.N.E. = D sin. 2 co.

Similarly, it may be shown that the value of E for the direction of ship's head is E cos. 2 co.

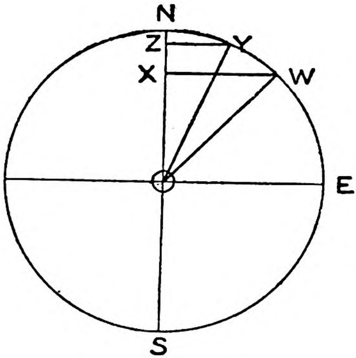


FIG. 76.

Table V., Appendix, facilitates this part of the work by enabling the values of B, C, D, and E for successive degrees to be taken out by inspection for each point of the compass. These values being merely the solution of a right angled plane triangle, it might be pointed out here that the traverse tables may be utilised also for this purpose by entering with each point in succession as a course, and with the value of the co-efficients in the distance column, the corresponding departure and difference of latitude columns will give the respective values of B and C. Similarly, with double the azimuth of the ship's head as a course, and the value of D and E as a distance, their values on each point of the compass will be found respectively in the departure and difference of latitude columns.

EXAMPLE VI.

118. Given the following deviations for ship's head by compass, determine the values of co-efficients A, B, C, D, and E, and from them calculate a table of deviations for each point of the compass:—

Deviation on	N. (4° W.)	S. (4° E.)
	N.E. (17° E.)	S.W. (10° W.)
	E. (20° E.)	W. (22° W.)
	S.E (14° E.)	N.W. (22° W.)

Proceed with the work as follows:

(1) Find the co-efficients as explained in par. 115.

(2) Arrange a table and head the columns as in Example VI.

(3) Write down in col. 1 the courses for which deviation is required.

(4) In col. 2 fill in the value and sign of *A*, which is constant.

(5) In cols. 3, 4, 5. and 6, write down the maximum and minimum values of *B*, *C*, *D*, and *E*, as shown in heavy type, taking care to attach the proper signs, being guided in this by the swing circles drawn at the head of the columns.

(6) Now, look up Table V. and at each point in succession, with the value of *B* (21°), copy down in col. 3, the respective values of *B*, namely 4·1 for 1 point, 8·0 for 2 points, and so on.

Then with the value of *C* (4°), copy down in col. 4 the respective values found under 7 points, 6 points, etc., namely 3·9, 3·7 etc.

Now with the value of *D* (3·7), copy down in col. 5 the respective values on 2, 4, and 6 points, and similarly in col. 6 write in the values of *E* as found under 6, 4, and 2 points.

It will be observed that there is a good deal of repetition in the entries, so having filled in the deviation for one cycle, the deviation on the remaining corresponding points is readily copied down.

(7) Lastly, add crosswise each line, and enter the algebraic sum in col. 7, then rewrite the deviations in col. 8, expressed in degrees and minutes, naming it *E*, when the sign is plus and *W* when it is minus. To turn the decimal figure into minutes, multiply it by six, thus:— $6·7° = 6° 42'$.

Exercise I.

With ship's head by compass, given the following deviations, determine the values of co-efficients *A*, *B*, *C*, *D*, and *E*, and from them calculate a table of deviations for each point of the compass:—

Deviations at	N. (21° E.)	S. (16° W.)
	N.E. (25° E.)	S.W. (20° W.)
	E. (19° E.)	W. (18° W.)
	S.E. (6° E.)	N.W. (3° E.)

EXAMPLE VI.

Dev. = $A + B$ Sin. Co. + C Cos. Co. + D Sin. 2 Co. + E Cos. 2 Co.
where Co. represents the direction of the ship's head.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Compass Course	° A − 0·5	° B + 21·0 B Sin. Co.	° C − 4 C Cos. Co.	° D + 3·7 D Sin. 2 Co.	° E + 0·5 E Cos. 2 Co.	Algebraic Sum. °	Calculated Dev. ° ′
N.	− 0·5	0·0	− 4·0	0·0	+ 0·5	− 4·0	4·0 W.
N. by E.	− 0·5	+ 4·1	− 3·9	+ 1·4	+ 0·4	+ 1·5	1·30 E.
N.N.E.	− 0·5	+ 8·0	− 3·7	+ 2·6	+ 0·3	+ 6·7	6·42 E.
N.E. by N.	− 0·5	+ 11·7	− 3·3	+ 3·5	+ 0·2	+ 11·6	11·36 E.
N.E.	− 0·5	+ 14·8	− 2·8	+ 3·7	− 0·0	+ 15·2	15·12 E.
N.E. by E.	− 0·5	+ 17·5	− 2·2	+ 3·5	− 0·2	+ 18·1	18·6 E.
E.N.E.	− 0·5	+ 19·4	− 1·5	+ 2·6	− 0·3	+ 19·7	19·42 E.
E. by N.	− 0·5	+ 20·6	− 0·8	+ 1·4	− 0·4	+ 20·3	20·18 E.
E.	− 0·5	+ 21·0	0·0	0·0	− 0·5	+ 20·0	20·0 E.
E. by S.	− 0·5	+ 20·6	+ 0·8	− 1·4	− 0·4	+ 19·1	19·6 E.
E.S.E.	− 0·5	+ 19·4	+ 1·5	− 2·6	− 0·3	+ 17·5	17·30 E.
S.E. by E.	− 0·5	+ 17·5	+ 2·2	− 3·5	− 0·2	+ 15·5	15·30 E.
S.E.	− 0·5	+ 14·8	+ 2·8	− 3·7	0·0	+ 13·4	13·24 E.
S.E. by S.	− 0·5	+ 11·7	+ 3·3	− 3·5	+ 0·2	+ 11·2	11·12 E.
S.S.E.	− 0·5	+ 8·0	+ 3·7	− 2·6	+ 0·3	+ 8·9	8·54 E.
S. by E.	− 0·5	+ 4·1	+ 3·9	− 1·4	+ 0·4	+ 6·5	6·30 E.
S.	− 0·5	0·0	+ 4·0	0·0	+ 0·5	+ 4·0	4·0 E.
S. by W.	− 0·5	− 4·1	+ 3·9	+ 1·4	+ 0·4	+ 1·1	1·6 E.
S.S.W.	− 0·5	− 8·0	+ 3·7	+ 2·6	+ 0·3	− 2·1	2·6 W.
S.W. by S.	− 0·5	− 11·7	+ 3·3	+ 3·5	+ 0·2	− 5·2	5·12 W.
S.W.	− 0·5	− 14·8	+ 2·8	+ 3·7	0·0	− 8·8	8·48 W.
S.W. by W.	− 0·5	− 17·5	+ 2·2	+ 3·5	− 0·2	− 12·5	12·30 W.
W.S.W.	− 0·5	− 19·4	+ 1·5	+ 2·6	− 0·3	− 16·1	16·6 W.
W. by S.	− 0·5	− 20·6	+ 0·8	+ 1·4	− 0·4	− 19·3	19·18 W.
W.	− 0·5	− 21·0	0·0	0·0	− 0·5	− 22·0	22·0 W.
W. by N.	− 0·5	− 20·6	− 0·8	− 1·4	− 0·4	− 23·7	23·42 W.
W.N.W.	− 0·5	− 19·4	− 1·5	− 2·6	− 0·3	− 24·3	24·18 W.
N.W. by W.	− 0·5	− 17·5	− 2·2	− 3·5	− 0·2	− 23·9	23·54 W.
N.W.	− 0·5	− 14·8	− 2·8	− 3·7	0·0	− 21·8	21·48 W.
N.W. by N.	− 0·5	− 11·7	− 3·3	− 3·5	+ 0·2	− 18·8	18·48 W.
N.N.W.	− 0·5	− 8·0	− 3·7	− 2·6	+ 0·3	− 14·5	14·30 W.
N. by W.	− 0·5	− 4·1	− 3·9	− 1·4	+ 0·4	− 9·5	9·30 W.

Exercise II.

From the following deviations, compute the co-efficients *A*, *B*, *C*, *D*, and *E*, and from them calculate the deviation on every alternate point of the compass starting at North :—

Deviation on	N.	(15° W.)	S.	(17° E.)
	N.E.	(21° W.)	S.W.	(20° E.)
	E.	(6° W.)	W.	(8° E.)
	S.E.	(4° E.)	N.W.	(7° W.)

Exercise III.

Calculate the deviation on each point of the compass from E. to W., by way of south, from the following deviations:—

Deviation on	N.	(18° W.)	S.	(12° E.)
	N.E.	(12° W.)	S.W	(18° E.)
	E.	(3° W.)	W.	(7° E.)
	S.E.	(6° E.)	N.W.	(10° W.)

ANSWERS.

Exercise I.

A + 1°·5, *B* + 18°·5, *C* + 18°·5, *D* − 1°·0, *E* + 1°·0.

Deviations.—21° 0′ E., 23° 42′ E., 25° 42′ E, 26° 42′ E., 26° 42′ E., 25° 54′ E., 24° 30′ E., 21° 54′ E., 19° 00′ E., 15° 30′ E., 11° 30′ E., 7° 6′ E., 2° 30′ E., 2° 18′ W., 7° 6′ W., 11° 42′ W., 16° 0′ W., 19° 42′ W., 22° 42′ W., 24° 4-′ W., 25° 6′ W., 25° 30′ W., 24° 6′ W., 21° 30′ W., 18° 0′ W., 13° 30′ W., 8° 48′ W., 3° 6′ W., 2° 30′ E., 7° 54′ E., 12° 54′ E., 17° 18′ E.

Exercise II.

A + 1°, *B* − 7°, *C* − 16°, *D* + 0·5, *E* 0°.

Deviations.—15° 0′ W., 16° 12′ W., 14° 42′ W., 11° 18 W., 6° 0′ W., 0° 18′ E., 6° 54′ E., 12° 48′ E., 17° 0′ E., 18° 48′ E., 17° 42′ E., 13° 54′ E, 8° 0′ E., 1° 6′ E., 5° 54′ W., 11° 24′ W.

Exercise III.

A − 0·5°, *B* − 5·0°, *C* − 15·0°, *D* + 2·5°, *E* − 2·5°.

Deviations.—3° 0′ W, 1° 12′ W., 0° 36′ E., 2° 18′ E., 4° 6′ E., 5° 54′ E., 7° 54′ E., 9° 54′ E., 12° 0′ E., 13° 54′ E., 15° 18′ E., 16° 6′ E., 16° 6′ E., 15° 18′ E., 13° 24′ E., 10° 36′ E., 7° 0′ E.

119. Heeling Error.—It has to be remembered that the heeling error is greatest on N. and S courses, decreasing as the cosine of the course to zero on E. and W.; it thus resembles the semi-circular deviation of co-efficient *C*.

If a ship changes tacks, still heading on the same course, the heeling error changes its name. When she changes from northerly to southerly courses, remaining on the same tack, it changes its name, but not if she changes her tack. The rules for naming heeling error may be written as follows:—

Same semi circle, same tack—same sign.
Same semi-circle, change tack—change sign.
Same tack, change semi circle—change sign.
Change tack, change semi-circle—same sign.

Thus a change of either the semi-circle or of the tack, but not of both, causes the heeling error to change its name. Semi-circle in this sense refers to the N. and S. semi-circles.

EXAMPLE VII.

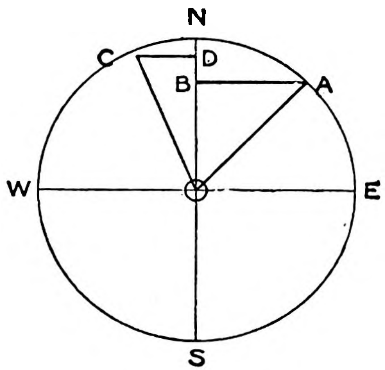


FIG. 77.

On port tack, heading N.E., and heeling 12°, the error was $-10°$. find the error when on starboard tack heading N.N.W. and heeling 16°.

In fig. 77, if $O\,N$ represents the heeling error on N.,

then $O\,B$ „ „ N.E.

and $O\,D$ „ „ N.N.W.

$O\,C = O\,A$, radii of same circle.

In triangle $O\,D\,C$, $O\,D = O\,C$ cos. $N\,O\,C$ I.

In triangle $O\,B\,A$, $O\,B = O\,A$ cos. $N\,O\,A$ II.

Divide I. by II. and cancel OA into OC, $\frac{OD}{OB} = \frac{\text{cos. } NOC}{\text{cos. } NOA}$ III.

$$\therefore O\,D = O\,B \text{ cos. } N\,O\,C \text{ sec. } N\,O\,A$$

This equation may be written, $\frac{\text{2nd error}}{\text{1st error}} = \frac{\text{cos. 2nd course}}{\text{cos. 1st course}}$

$$\therefore \frac{\text{2nd error}}{10} = \frac{\text{nat. cos. 2 pts.}}{\text{nat. cos. 4 pts.}}$$

$$\text{2nd error} = \frac{10 \times \cdot 923}{\cdot 71} = 13^\circ$$

The error on N.N.W. is therefore 13°, when the angle of heel is the same, but the error varies directly as the heel, so the

$$\frac{\text{new error}}{\text{old error}} = \frac{\text{new heel}}{\text{old heel}}$$

$$(i.e.)\ \frac{x}{13} = \frac{16}{12}$$

$$\therefore x = \frac{13 \times 16}{12} = 17\tfrac{1}{3}^\circ$$

Answer.— $+\,17\tfrac{1}{3}^\circ$, the sign is changed because changed tacks in the same semi-circle.

Example VIII.

When heading N.E. by E., and heeling 8°, the error was $+\,4^\circ$. Find the error when heading S.S.W., on the same tack, and heeling 18°.

In fig. 78, if $O\,S$ represents the heeling error on S.,

then $O\,D$ „ „ S.S.W.

and $O\,B$ „ „ N.E. by E.

Note.—For natural sines, cosines, etc., *see* Table I. Appendix.

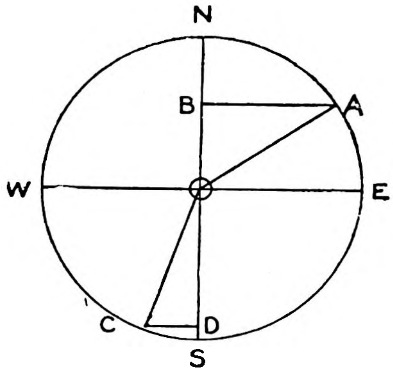


FIG. 78.

$$OD = OC \cos. SOC \qquad \text{I.}$$
$$OB = OA \cos. NOA \qquad \text{II.}$$

Dividing I. by II. $\dfrac{OD}{OB} = \dfrac{\cos. SOC}{\cos. NOA}$

$$\frac{\text{2nd error}}{\text{1st error}} = \frac{\text{cos. 2nd course}}{\text{cos. 1st course}}$$

$$\therefore \text{ 2nd error} = \frac{4 \times \text{nat. cos. 2 pts.}}{\text{nat. cos. 5 pts.}}$$

$$\text{2nd error} = \frac{4 \times {}^{\cdot}923}{{}^{\cdot}559} = 6{\cdot}6^{\circ}$$

but $\dfrac{\text{new error}}{\text{old error}} = \dfrac{\text{new heel}}{\text{old heel}} \therefore \dfrac{x}{6{\cdot}6} = \dfrac{18}{8}$, $\quad x = 14{\cdot}85^{\circ}$

Answer.— $-14{\cdot}85^{\circ}$, sign changed because on same tack, but changed the semi-circle.

EXERCISE I.

Heading S.W. by W., error $+5^{\circ}$, heeling 20° on port tack, find error when heading E.N.E., heeling 10° on starboard tack.

Answer.— $+1{\cdot}75^{\circ}$.

EXERCISE II.

Heading N.E. $\frac{1}{2}$ N., error $-8°$, heeling $15°$ on the starboard tack, find error when heading N. by W. and heeling $6°$ on the same tack.

Answer.—$-4·04°$.

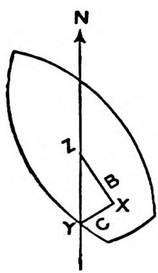
EXERCISE III.

Heading south, error $+15°$, heeling $23°$ on port tack, find the error on E. $\frac{1}{2}$ N., heeling $10°$ on the starboard tack.

Answer.—$+·7°$.

EXAMPLE IX.

120. A ship's head in the building yard was N.W. by N., and co-efficient B, due to sub-permanent magnetism, was $12°$, find the value of C, and give the signs for both co-efficients.



$+B$ indicates	head	Southerly	
$-B$	,,	,,	Northerly
$+C$	,,	,,	Easterly
$-C$	,,	,,	Westerly

FIG. 79.

In fig. 79 Y represents the position of the sub-permanent red pole.
$X\ Y$, the athwartship component (co-eff C).
$Z\ X$, the fore and aft component (co-eff. B).
^{L}Z, the direction of head in building yard.
In triangle $Z\ X\ Y$, $X\ Y = Z\ X$ tan. Z.

$$C = 12 \times \text{nat tan. } 3 \text{ pts.}$$
$$C = 12 \times ·67.$$
$$C = 8·04°.$$

$C = -8°$ because the needle is attracted to the port side.
$B = -12°$ because the needle is attracted to the stern.

The value of C may also be found by inspection of the Traverse Tables.

Enter with head in building yard as a course (N.W. × N).
Coeff. B in difference latitude column (12°).
Coeff. C is found in departure column (8°).

EXAMPLE X.

Given $C+25°$, and $B+14°$, what was the direction of ship's head whilst building?

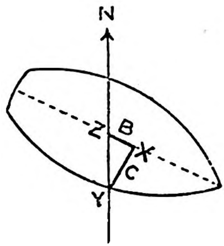


FIG. 80.

By inspection.—Enter Traverse Table with 25 as dep., and 14 as diff. lat., and the corresponding angle (61°) is the required direction S. 61° E., because B is plus and C is plus. (*See* par. 58.)

By calculation:—In triangle $Z\,X\,Y$ (fig. 80)

$$\text{Nat. tan. } Z = \frac{C}{B} = \frac{25}{14} = 1{\cdot}8 \quad \therefore Z = 61°$$

The maximum deviation due to hard iron is represented by ZY and may be found in the distance column of the traverse table,

or $ZY^2 = ZX^2 + XY^2$

$\therefore ZY = \sqrt{B^2+C^2} = \sqrt{14^2+25^2} = 28{\cdot}7°$

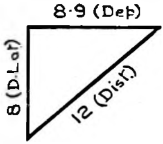
EXAMPLE.

Given Dev. 8° E. when heading East on the magnetic equator and when heading N.E. the Dev. is 12° E. If coefficient D be properly corrected find the maximum deviation due to hard iron.

The value of B, on N.E. = B Sin Co. = 8 Sin 45° = 8 × ·71 = 5·7
Total Dev. on N.E. = 12·0° E.
B on N.E. = 5·7 E.

Value of C on N.E. = 6·3 E.

$$\text{Coeff. } C = \frac{6\cdot3}{\text{Cos. } 45} = \frac{6\cdot3}{\cdot71} = 8\cdot9^\circ \text{ value heading North.}$$



Max. Dev. $= \sqrt{8\cdot9^2+8^2} = 12^\circ$
or, enter traverse table with Dep. 8·9, *D* Lat. 8, and in Dist. Col. find 12° the maximum deviation due to hard iron.

Exercise I.

(1) Head in building yard N.E., coefficient $B=17^\circ$. Find value and sign of coefficient C.

(2) Head S.S.W., $C=6^\circ$. Find B.

(3) Head W.N.W., $B=12^\circ$. Find C.

(4) Given $B-12^\circ$, $C+16^\circ$. Find direction of ship's head in building yard, also maximum deviation due to hard iron.

Answers.—(1) $B-17^\circ$, $C+17^\circ$, (2) $B+14\cdot8^\circ$, $C-6^\circ$, (3) $C-28\cdot6^\circ$, $B-12^\circ$. (4) N. 53° E., 20°.

ANSWERS.

Exercise I.

(1) *Capella* and *Markab*, E.; *Arcturus*, α *Ursae Majoris* and γ *Ursae Majoris*, W.; *Arcturus*, W.H.A. 5h. 6m. 13s.; true azimuth N. 89° 45′ W., deviation 7° 45′ W.

(2) *Castor*, α *Orionis*, α *Ursac Majoris*, *Aldebaran*, E.; *Vega*, *Altair*, W.; *Aldebaran*, E.H.A. 3h. 40m. 36s.; true azimuth N. 110° 43′ E., deviation 1° 17′ W.

121. The Effect of a Magnet.—When both poles of a magnet act on a compass needle the angle of deflection, when small, varies inversely as the cube of the distance between the centres of the magnet and needle.

Example.

If a magnet corrects 8° deviation when placed broadside on at a distance of 24 inches from the centre of a compass, how many degrees should it correct when 16 inches from the compass?

$$\frac{\text{The new dev.}}{\text{The old dev.}} = \frac{(\text{old distance})^3}{(\text{new distance})^3}$$

$$\frac{\text{New dev.}}{8^\circ} = \left(\frac{24}{16}\right)^3 \therefore \text{dev.} = 8 \times \left(\frac{3}{2}\right)^3 = 27^\circ \textit{ Ans.}$$

When the angle of deflection is large a more accurate result is found by the Law of Tangents (see page 214), so that the natural tangent of the deviation should be substituted in the foregoing example, and the equation becomes:—

$$\frac{\text{Nat. tan dev.}}{\text{Nat. tan. } 8^\circ} = \left(\frac{24}{16}\right)^3 = 3{\cdot}38$$

Nat. tan. dev.$=$Nat. tan. $8^\circ \times 3{\cdot}38 = {\cdot}14 \times 3{\cdot}38 = {\cdot}4732$.

Dev.$=25{\cdot}3^\circ$ instead of 27°, a difference of $1{\cdot}7^\circ$.

Example.

A magnet corrects 12° deviation when 16 inches from the compass where must it be placed to correct 8° dev?

$$\frac{(\text{new dist.})^3}{(\text{old dist.})^3} = \frac{\text{old dev.}}{\text{new dev.}} = \frac{12}{8} = 1{\cdot}5$$

(new dist)$^3 = 16^3 \times 1{\cdot}5 = 6144$. Dist.$=\sqrt[3]{6144}$ by logs $= 18{\cdot}3$ inches. *Ans.*

The angle of deflection also varies directly as the sine of the angle between the magnetic meridian and the axis of the magnet when the distance is constant.

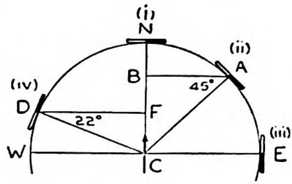


Fig. 84a.

In Fig. 84a, C represents the centre of the compass needle and $C\,N$ the magnetic meridian of the needle. (i) Assume a magnet at position N making an angle of 90° with the meridian. Its action will then produce the maximum deflection of the compass. Suppose the deviation thus produced to be 10° represented in magnitude by the length of CN drawn to any convenient scale of equal parts.

(ii) Move the magnet to position A so that $\angle NCA = 45^\circ$. The axis of the magnet now makes an angle of 45° with the meridian and CB represents the deviation it will produce.

But $CA = CN = 10^\circ$

and $CB = CA \sin BAC = 10 \sin 45^\circ = 10 \times {\cdot}7 = 7^\circ$ dev.

(iii) When the magnet is moved to position E its axis is parallel to the meridian and the angle between them is $0°$, but $\sin 0°=0$ and consequently there is no deflection of the needle.

(iv) But suppose the magnet were moved from A to position D so that the angle between the axis of the magnet and the meridian is $22°=\angle FDC$, then CF will represent the new deviation and the question may be written in the form of a problem as follows:—

EXAMPLE.

A magnet causes 7° deflection when it makes an angle of 45° with the meridian, what deviation would it correct when the angle is 22°?

$$\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{sine new angle}}{\text{sine old angle}}$$

$$\frac{\text{dev.}}{7°} = \frac{\sin 22°}{\sin 45°} = \frac{\cdot 37}{\cdot 71} = \cdot 52$$

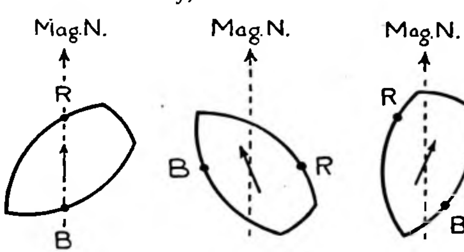
$$\text{dev.}=7°\times\cdot 52=3\cdot 64° \textit{ Ans.}$$

122. The Ship Acts Like a Magnet.

The deviation due to hard iron is zero when the ship is heading in the same direction as in building yard, or opposite to it, and this semi-circular deviation increases as the sine of the angle away from the zero, or neutral, direction attaining its maximum value when heading at right angles to the building direction.

Example.—If the maximum deviation due to hard iron is 16° W., when heading N. 40° W., required the direction of head whilst building, also deviation on S. 15° W.

The vessel's head was 90° either to right or left of N. 40° W. A rule to determine which way, is to remember that when the building



(i) (ii) (iii)

FIG. 76.

direction is to the right of the course the deviation is East, and when to the left it is West. Thus, if the maximum deviation on N. 40° W. is 16° W. the ship's head in building yard was 90° to the left, that is S. 50° W., in order to get a blue pole on port bow to cause the westerly deviation. This may be illustrated as follows:—

(i) Head S. 50° W. in building yard is the neutral point of no deviation, blue pole on port bow.

(ii) Head N. 40° W., maximum deviation (16° W.) because ship's poles are acting at right angles to the compass needle, blue pole causing West deviation.

(iii) Head S. 15° W., blue pole attracting needle to the right thus producing East deviation.

To find deviation on S. 15° W.

$$\frac{\text{new dev.}}{\text{max. dev.}} = \frac{\text{sine angle from neutral point}}{\sin 90^\circ} \quad \text{but sine } 90^\circ = 1$$

$$\therefore \quad \text{dev.} = 16^\circ \times \text{sine } 35^\circ = 16 \times {\cdot}57 = 9{\cdot}1^\circ \text{ East.}$$

This may be illustrated as follows:—

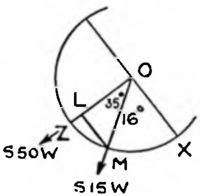


FIG. 77.

In Fig.

If OX = max. dev. and Z is the neutral point (S. 50° W.)
then LM = dev. on S. 15° W.
$LM = OM$ sin. $35^\circ = 16 \times {\cdot}57 = 9{\cdot}1^\circ$ E.

Maximum deviation due to hard iron 20° E. when heading N. 30° E. Find head when building, also deviation when heading S. 20° E.

Deviation being East, head in building yard was 90° to right of N. 30° E., viz., S. 60° E.

New dev. = max. dev. × sine angle from neutral point.
$= 20^\circ \times \sin 40^\circ = 20 \times {\cdot}64 = 12{\cdot}8^\circ$ W.

Deviation is West because neutral point is to left of S. 20° E. If a figure be drawn with ship's head S. 20° E., showing a blue pole 30° before the starboard beam, the name of the deviation will be obvious.

EXERCISES.

(1) A deflection of 7° is caused by a magnet when 18 inches removed from the compass, how many degrees will it deflect the needle when 22 inches away from the centre of the card?

Ans. 3·8°.

(2) At a distance of 20 inches a magnet deflects the compass needle 5°, what will be the deflection when it is 15 inches away from the needle?

Ans. 11·8°.

(3) A magnet when "broadside on" caused a deflection of 12°, the distance between the centre of the compass card and the middle of the magnet being 20 inches, find the deflection it would cause when "end on" if the distance were 16 inches.

Ans. $\begin{cases} 23{\cdot}4° \text{ if broadside on.} \\ 46{\cdot}8° \text{ if end on.} \end{cases}$

(4) A magnet deflects the compass needle 8½° when its angle is 90° with the meridian, what deviation will it correct when the angle is 30°?

Ans. 4·25°.

(5) If the deflection is 10° when the magnet makes an angle of 60° with the meridian, what will the deflection be when the angle is 20°?

Ans. 4°

(6) If maximum deviation due to hard iron was 25° W. when heading S. 40° W., required direction of ship's head whilst building, also the deviation when heading N. 20° W.

Ans. S. 50° E., dev. 12½° E.

(7) Maximum deviation 15° E. heading N. 50° W., required the deviation on (i) S. 80° E., (ii) S. 80° W.

Ans. (i) 11·55° W. (ii) 9·6° E.

123. Vibrating Needle Experiment.—(103-106.)

EXAMPLE.

A horizontal vibrating needle made 10 vibrations in 40 seconds on shore. The same number of vibrations were made at three different positions on board; at *A* it occupied 45 seconds, at *B* 50 seconds, and at *C* 63 seconds; compare the directive

force of the compass at positions A, B, and C with the earth's normal force.

The directive force of the ship and earth combined varies inversely as the square of the times occupied by a needle in making an equal number of vibrations on shore and on board.

$$\frac{\text{Force on board}}{\text{Force on shore}} = \frac{(\text{shore time})^2}{(\text{ship time})^2} = \frac{(40)^2}{(45)^2} = \cdot 79 \text{ for } A$$

$$\text{,,} \quad = \frac{(\quad \text{,,} \quad)^2}{(\quad \text{,,} \quad)^2} = \frac{(40)^2}{(50)^2} = \cdot 64 \text{ for } B$$

$$\text{,,} \quad = \frac{(\quad \text{,,} \quad)^2}{(\quad \text{,,} \quad)^2} = \frac{(40)^2}{(63)^2} = \cdot 4 \text{ for } C$$

The directive force is greatest at A, being about eight-tenths of the earth's force, while at B it is about six-tenths, and at C only four-tenths, the earth's force at the place being taken as unity.

EXAMPLE.

The time of 10 vibrations on shore was 53 seconds, and on board 62 seconds, the deviation for ship's head being 25°; find value of ship's relative horizontal force (H_1).

$$H_1 = \frac{(\text{shore time})^2}{(\text{ship time})^2} \times \text{cos. dev.} = \frac{(53)^2}{(63)^2} \times \cos 25^\circ$$

$$= \cdot 73 \times \cdot 91 = \cdot 664$$

EXERCISES.

(1) A needle occupies 55 seconds in making 10 vibrations on shore, and 66 seconds on board, express the directive force of the compass needle for that direction of ship's head, in terms of the earth's horizontal force at that place.

Ans. As 1 is to ·69.

(2) A certain number of vibrations occupied 92 seconds on shore, and only 78 seconds when placed in the binnacle on board, find the value of H_1, for the direction of ship's head, the deviation being 20°.

Ans. 1·27.

(3) Time of x vibrations on shore 50 seconds, on board 60 seconds, deviation for ship's head 15°, find H_1.

Ans. ·67.

124. The Earth's Horizontal Force.—(Refer to par. 35-39.)

EXAMPLE.

The maximum deviation due to hard iron is 14° E. when the ship is at Glasgow; what would be its value, due to the same cause, when heading in the same direction at Malta, and at Sydney, N.S.W.?

Refer to Chart. III., which shows lines of equal horizontal force, and note that the H.F. at the Clyde, Malta, and Sydney is 0·9 and 1·4, and 1·5, respectively.

The magnetic intensity of hard iron remains constant, but the directive force of the needle varies directly as the earth's horizontal force, therefore, the deviation from hard iron will decrease as the directive force of the needle increases, in other words, the deviation varies inversely as the horizontal force.

$$\therefore \frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{H.F. at old place}}{\text{H.F. at new place}}$$

$$\text{At Malta, new dev.} = \frac{\text{old dev.} \times \text{H.F. at Clyde}}{\text{H.F. at Malta}} = \frac{14 \times 0{\cdot}9}{1{\cdot}4} = 9 \text{ E.}$$

$$\text{At Sydney, new dev.} = \frac{14 \times 0{\cdot}9}{1{\cdot}5} = 8{\cdot}4 \text{ E.}$$

The deviation retains the same name in all latitudes because hard iron does not change its polarity.

EXERCISE.

The maximum deviation from hard iron alone was 9° W. when at Melbourne; what would be the maximum error from the same cause when heading in the same direction at Cape Town, Demerara, London, and Archangel?

Ans. Melbourne, H.F.=1·3, dev. 9° W. Cape Town, H.F. =1, dev. 11·7° W. Demerara, H.F.=1·6, dev. 7·3° W. London, H.F.=1, dev. 11·7° W. Archangel, H.F.=·8, dev. 14·6° W.

125. The Earth's Vertical Force.

EXAMPLE.

At Malta the deviation due to vertical soft iron was 6° W. (induced *B*) when heading West, find the deviation due to the same cause when heading in the same direction at Colombo, Suez, and Fremantle.

The deviation due to vertical soft iron varies directly as the tangent of the dip, and changes its name when the equator is crossed (*see* par. 62), therefore $\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{tan. dip at new place}}{\text{tan. dip at old place}}$

Refer to Chart II., and note that the dip at Malta is 50°, at Colombo 6°, at Suez 38°, and at Fremantle 63°.

$$\text{For Colombo, } \frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{tan. dip at Colombo}}{\text{tan. dip at Malta}}$$

$$\therefore \text{dev.} = \frac{6^\circ \text{ W.} \times \text{nat. tan. } 6^\circ}{\text{nat. tan. } 50^\circ} = \frac{6 \times \cdot 11}{1 \cdot 19} = \cdot 55^\circ \text{ E.}$$

The deviation is now opposite in name, because the ship has crossed the magnetic equator.

$$\text{For Suez, dev.} = \frac{6^\circ \text{ W.} \times \text{nat. tan. } 38^\circ}{\text{nat. tan. } 50^\circ} = \frac{6^\circ \times \cdot 78}{1 \cdot 19} = 3 \cdot 9^\circ \text{ W.}$$

Deviation retains the same name, ship being still in the same hemisphere.

$$\text{For Fremantle, dev.} = \frac{6^\circ \text{ W.} \times \text{nat. tan. } 63^\circ}{\text{nat. tan. } 50^\circ} = \frac{6^\circ \times 1 \cdot 9}{1 \cdot 19} = 9 \cdot 9^\circ \text{ E.}$$

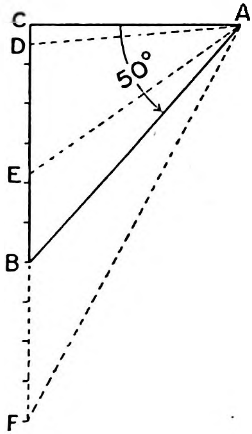


Fig. 85.

Approximate answers may be found by construction as follows:—

$\angle CAB$ = dip at Malta 50°, and CB the given dev. = 6° W.

$\angle CAD$ = dip at Colombo 6°, and CD = 0·5° E. dev.

$\angle CAE$ = dip at Suez 38°, and CE = 3·9° W. dev.

$\angle CAF$ = dip at Fremantle 63°, and CF = 9·9° E. dev.

EXERCISES.

(1) The maximum deviation due to vertical soft iron was 8° E. when heading East at Cape Town, find its value when heading in the same direction at Buenos Ayres, Gibraltar, and Glasgow.

(2) When heading East at New York the deviation due to vertical soft iron was 10° E., find the deviation it would produce when heading West at Panama, Callao, and Valparaiso.

NOTE.—The semi-circular deviation due to soft iron changes its name when the course is reversed, as well as changing its name on crossing the equator.

Ans. (1) Cape Town, dip 58°, dev. 8° E. Buenos Ayres, dip 27°, dev. 2·5° E. Gibraltar, dip 55°, dev. 7·15° W. Glasgow, dip 70°, dev. 13·7° W.

Ans. (2) New York, dip 70°, dev. 10° E. Panama, dip 30°, dev. 2·1° W. Callao, dip 0°, dev. 0° Valparaiso, dip 30°, dev. 2·1° E.

EXAMPLE.

The deviation due to vertical iron in the fore and aft line is 8° E. when heading East, find its value when heading N.W. by W.

The semi-circular deviation due to this vertical iron is coefficient B, which attains its maximum value when the ship is heading E. or W., and decreases as the sine of the azimuth of ship's head to zero on N. and S. courses (par. 63-64).

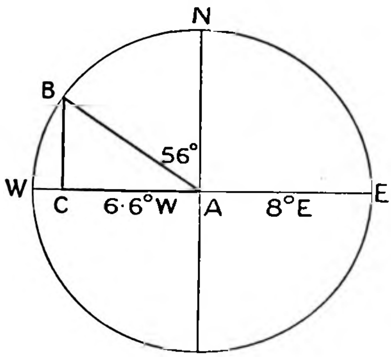


FIG. 86.

In fig. 86, if AE represents the dev. on E. or W., then AC represents the dev. on N.W. by W.

$$AC = AB \text{ sin. } NAB$$
$$AC = 8 \text{ nat. sin. } 56°$$
$$AC = 8 \times \cdot 83$$

∴ dev. on N.W. by W. $= 6{\cdot}64°$ W.

The deviation changes its name on changing from easterly to westerly courses.

EXAMPLE.

A compass at Plymouth has 12° W. dev. from vertical iron (induced B) when heading West, find the deviation arising therefrom when heading N.E. at Quebec and at Cape Town.

From Chart II., dip at Plymouth is 67°, at Quebec 78°, and at Cape Town 58°.

$$\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{tan. dip at new place}}{\text{tan. dip at old place}} \times \text{sin. course}$$

$$\text{For Quebec, dev.} = \frac{12^\circ \text{ W.} \times \text{nat. tan. } 78^\circ \times \text{nat. sin. } 45^\circ}{\text{nat. tan. } 67^\circ}$$

$$\text{Dev.} = \frac{12^\circ \times 4\cdot7 \times \cdot71}{2\cdot35} = 17\cdot04^\circ \text{ E.}$$

Deviation is of opposite name, for although ship is in the same hemisphere her head is changed from west to easterly.

$$\text{For Cape Town, dev.} = \frac{12^\circ \times \text{nat. tan. } 58^\circ \times \text{nat. sine } 45^\circ}{\text{nat. tan. } 67^\circ}$$

$$\text{Dev.} = \frac{12 \times 1\cdot6 \times \cdot71}{2\cdot35} = 5\cdot7^\circ \text{ W.}$$

The deviation is the same name in this case because it has undergone a double change. It changed from W. to E. on crossing the equator, and from E. back again to W. when the ship's head was altered from west to easterly.

EXERCISE.

A vessel at Gibraltar has 10° E. dev. from vertical soft iron when heading E., find the dev. due to the same cause when heading N.N.W. and S.E. at Belfast and Rio de Janeiro.

Ans. Belfast dip 70°, dev. 7·2° W. and 13·6° E.; Rio Janeiro dip 15°, dev. 0·7° E. and 1·3° W.; Gibraltar dip 55°.

126. Separation of Coefficient *B*.

EXAMPLE.

In an uncompensated compass there is no deviation from hard iron when heading S.E. by S., the deviation on East is +12°, and on North it is 5°. Find the value of induced B.

There being no deviation due to hard iron when heading S.E. by S. indicates that the ship's head in building yard was either S.E.

by S. or N.W. by N., these being the zero points for sub-permanent deviation in this case, but as the deviation given on East is the value of $+B$, which represents an attraction of the needle towards the bow, the ship's head must have been southerly to develop a blue sub-permanent pole at the fore end of the ship, therefore, of the two directions her head must have been S.E. by S. The question now reads, head in building yard S.E. by S. $+C=5°$, find sub-permanent B.

$$
\begin{array}{rl}
& B=C \text{ cot head in building yard.} \\
& B=5 \text{ cot 3 points.} \\
& B=5+1{\cdot}48. \\
& B=+\ \ 7{\cdot}4 \text{ due to hard iron.} \\
\text{Total} & B=+12{\cdot}0 \text{ when heading east.} \\
\text{Induced} & B=\underline{\overline{+4{\cdot}6°}} \text{ due to vertical iron.}
\end{array}
$$

EXAMPLE.

The ship's head in a building yard at Greenock was S. 34° W.; the maximum deviation due to hard iron on swinging ship is found to be 14°, the horizontal force being ·9. Find the deviation, with sign, due to hard iron at Pernambuco when heading North, the horizontal force then being 1·4.

The ship's head when building being S. 34° W. ($+B$ and $-C$) the maximum deviation due to hard iron will appear when heading at right angles to that direction. The deviation is therefore 14° E. on S. 56° E., and 14° W. on N. 56° W. We have now to find the value of coefficient C (the dev. on North) from the equation

$$
\begin{array}{rl}
\text{Dev.} & =B \text{ sin. co.}+C \text{ cos. co.} \\
\text{but } B & =C \times \text{cot. head in building yard} = C \text{ cot } 34°. \\
\therefore 14° & =C \text{ cot. } 34° \text{ sin. } 56°+C \text{ cos. } 56°. \\
14° & =C\ (\text{cot. } 34° \text{ sin. } 56°+\text{cos. } 56°). \\
C & = \dfrac{14°}{1{\cdot}48\times{\cdot}83+{\cdot}56} \\
C & = -\ 7{\cdot}82.°
\end{array}
$$

and the deviation due to hard iron would have been $-7{\cdot}82°$ when heading North at Pernambuco had the earth's horizontal force there

been the same as at Greenock, but the deviation varies inversely as the H.F. so that, $\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{old H.F.}}{\text{new H.F.}}$

$$\text{dev.} = \cdot 9 \times 7\cdot 82 \div 1\cdot 4 = -5\cdot 03^\circ$$

Dev. on North at Pernambuco is therefore 5·03° W.

Exercises.

(1) The deviation due to hard iron on S.W. by W. is nil, the compass being uncompensated; the deviation on West is -9° and on South $+9^\circ$. Find how much of coefficient B is due to vertical iron.

(2) In an uncompensated compass there is no deviation on S.S.E. due to hard iron, the deviation on North is -4° and on East -8°. Find sub-permanent B and induced B.

(3) A ship built at New York heading N. 50° E. The maximum deviation due to hard iron is 12°, H.F. $= \cdot 9$, find the deviation with sign due to hard iron at Cape Town when heading North, the H.F. being 1.

Ans. (1) $B = +6\cdot 03$ due to hard iron, $+2\cdot 97$ to soft iron.
(2) $B = -9\cdot 64$ due to hard iron and $+1\cdot 64$ to soft iron.
(3) At New York, dev. $= +9\cdot 18$ on North.
At Cape Town, dev. $= +8\cdot 26$ on North.

127. Computing Deviation for Ship's Head.

Example.

Given the deviation on North $= -4^\circ$, on West $= -21^\circ$, on N. 56° E. $= 18^\circ$ E. Find the deviation on N. 34° W.

From question the deviation on West is $+B$; on North it is $-C$.

Find (1) the deviation B and C together would produce on N. 56° E; the difference between this deviation and the total deviation (18°) will be the amount due to horizontal iron.

(2) Find the value of D.

(3) Find the deviation on N. 34° W.

(1) Dev. $= B$ sin. co. $+$ C cos. co.

Dev. on N. 56° E. $= 21 \times \sin. 56^\circ + 4 \times \cos. 56^\circ.$
$= 21 \times \cdot 83 + 4 \times \cdot 56$
apply coefficient signs for N. 56° E.
$= + 17\cdot 43 - 2\cdot 24.$
Dev. on N. 56° E. $= + 15\cdot 2$ due to B and C.
Total dev. $= + 18\cdot 0$

Dev. on N. 56° E. $= + 2\cdot 8$ due to horizontal iron.

(2) Given the quadrantal deviation on N. 56° E.$= + 2\cdot8°$, find the value of coefficient D.

$$\text{Dev.} = D \text{ sin. } 2 \text{ co.}$$
$$2\cdot8 = D \text{ sin. } 112° \therefore D = \frac{2\cdot8}{\cdot93} = 3°$$

(3) Given B, C and D, find deviation on N. 34° W.

$$\text{Dev.} = B \text{ sin co.} + C \text{ cos. co.} + D \text{ sin } 2 \text{ co.}$$
$$\text{Dev. on N. } 34° \text{ W.} = 21 \text{ sin. } 34° + 4 \text{ cos. } 34° + 3 \text{ sin. } 68°.$$
$$\text{,,} \quad = 21 \times \cdot56 + 4 \times \cdot83 + 3 \times \cdot93.$$
,, apply coeff. signs for N. 34° W.
$$\text{,,} \quad = -11\cdot76 - 3\cdot32 - 2\cdot79$$
$$\text{Dev. on N. } 34° \text{ W.} = -17\cdot87°.$$

Exercises.

(1) Given deviation on North$=10°$ E., on West$=4°$ E., on N. 40° E.$=14°$ E. Find deviation on N. 30° W.

(2) Given deviation on East $= -6°$, on North $= -15°$, on N. 67° W.$= +1$. Find the deviation on N. 23° W.

ANSWERS.

(1) Dev. on N. 40° E. due to B and $C = +5\cdot1$ and to hor. iron $+8\cdot9$. Coefficient $D = 9°$. Dev. on N. 30° W.$= +2\cdot9°$.

(2) Dev. on N. 67° W. due to B and $C = -0\cdot33°$, and to hor. iron $+1\cdot33$. Coefficient $D = +1\cdot85°$. Dev. on N. 23° W.$= -10\cdot1°$.

128. Deviation from B, C and D and change of Latitude.

Example.

At Calcutta the deviation on North$= +12°$, on East$= -8°$, on N.E. $= +9°$, on S.W. $= -1°$, H.F. $= 2$, dip$=30°$. Find the deviation on N. 60° W. at Port Said when H.F.$=1\cdot6$ and dip$=42°$.

From the question, at Calcutta $B = -8°$, $C = +12°$, $D = +4°$. find the deviation on N. 60° W., neglecting induced B.

$$\text{Dev.} = B \text{ sin. co.} + C \text{ cos. co.} + D \text{ sin. } 2 \text{ co.}$$
$$\text{Dev. on N. } 60° \text{ W.} = 8 \text{ sin. } 60° + 12 \text{ cos. } 60° + 4 \text{ sin. } 120°.$$
$$= 8 \times \cdot866 + 12 \times \cdot5 + 4 \times \cdot866.$$
apply coefficient signs for N. 60° W.
$$= +6\cdot928 + 6\cdot0 - 3\cdot464 = 12\cdot93 - 3\cdot464.$$

The quadrantal deviation 3·464 (D sin. 2 co.) remains the same in all latitudes because the induced magnetism in the horizontal iron which causes this deviation and the directive force of the compass needle both depend on the earth's H.F., and so they maintain the same ratio to each other. But the semi-circular deviation 12·93 (B sin. co.$+C$ cos. co.) varies inversely as the H.F., so that at Port Said,

$$\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{old H.F.}}{\text{new H.F.}}$$

$$\text{Dev.} = 12{\cdot}93 \times 2 \div 1{\cdot}6 = 16{\cdot}2^\circ.$$

$$\text{Dev. on N. } 60^\circ \text{ W.} = +16{\cdot}20 \text{ due to hard iron.}$$

$$\text{,,} \qquad = -3{\cdot}46 \text{ due to hor. soft iron.}$$

The total dev. on N. 60° W$=\underline{+12{\cdot}74^\circ}$

Exercises.

(1) At Cape Town, given H.F.$=1$; dip$=60^\circ$; dev. on South$=+16^\circ$, on West$=-10^\circ$, on N.E.$=-1^\circ$, on S.W.$=+7^\circ$. Find the deviation on N. 25° E. at Malta where the H.F.$=1{\cdot}5$ and dip$=50^\circ$.

(2) At New York, given H.F.$=1{\cdot}2$; dip$=70^\circ$; dev. on North$=+10^\circ$, on East $=-10^\circ$, on N.E. $=+5^\circ$, on S.W. $=-1^\circ$. Find the deviation on N. 34° E. at Nagasaki where the H.F.$=1{\cdot}7$, and dip$=45^\circ$.

ANSWERS.

(1) At Cape Town, dev. $=-10{\cdot}27^\circ$ from hard iron, and $+2{\cdot}30^\circ$ from horizontal iron. At Malta, dev.$=-6{\cdot}85^\circ$ from hard iron, and $+2{\cdot}30^\circ$ from horizontal iron, the total dev.$=-4{\cdot}55^\circ$ on N. 25° E.

(2) At New York, dev. $=+2{\cdot}7^\circ$ from hard iron and $+1{\cdot}9^\circ$ from hor. iron. At Nagasaki, dev.$=+1{\cdot}9^\circ$ from hard iron and $+1{\cdot}9^\circ$ from hor. iron, the total dev. $=+3{\cdot}8^\circ$ on N. 34° E.

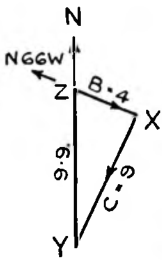
MISCELLANEOUS EXAMPLES.

Example I.

129. Miscellaneous Examples.

The deviation from hard iron on North$=10^\circ$ W., on East$=2^\circ$ W., on South$=8^\circ$ E., on West$=6^\circ$ E., the H.F. being ·9. Required the maximum deviation due to hard iron where H.F.$=1{\cdot}2$.

Dev.	Dev.	
On N. = 10° W.	On E. = 2° W.	(1) Find head when building.
,, S. = 8 W.	,, W. = 6 W.	(2) Find maximum deviation.
—	—	(3) Adjust deviation for change of H.F.
$-C=\underline{9}$	$-B\ \ \underline{4}$	



(1) tan head when building $=\frac{C}{B}=\frac{9}{4}=2{\cdot}25$

∴ Head N. 66° W.

(2) Max. dev. $=\sqrt{81+16}=\sqrt{97}=9{\cdot}8$

In fig.

If ZX = dev. due to attraction to stern (4°)
and XY = ,, ,, to port (9°)
then ZY = max. dev. $=\sqrt{XY^2+ZX^2}$ as above.

(3) $\frac{\text{new dev.}}{\text{old dev.}}=\frac{\text{old H.F.}}{\text{new H.F.}}=\frac{{\cdot}9}{1{\cdot}2}={\cdot}75$

∴ Dev. $=9{\cdot}9\times{\cdot}75=7{\cdot}4°$. *Ans.*

Example II.

Deviation due to hard iron 10° W., ship heading N. 30° E., dip +56°. Find deviation on same course when dip is −70°.

The deviation due to hard iron varies inversely as the earth's H.F. and the H.F. varies as the cosine of the dip.

$$\frac{\text{new dev.}}{\text{old dev.}}=\frac{\text{old H.F.}}{\text{new H.F.}}=\frac{\text{cos old dip }(+56°)}{\text{cos new dip }(-70°)}=\frac{{\cdot}559}{{\cdot}342}=1{\cdot}63$$

Dev. $=10°\times1{\cdot}63=16{\cdot}3°$ W. *Ans.*

Deviation due to hard iron retains the same signs in both hemispheres.

Example III.

If $b=5°$ E. when heading S.W. by S., dip +70°, find value of b on N.E. by E. and dip −50°.

(1) Adjust value of b for change of head.

(2) Adjust the new value for change of dip.

$$(1)\ \frac{\text{new dev.}}{5} = \frac{\sin \text{N.E.}\times\text{E.}}{\sin \text{S.W.}\times\text{S.}} = \frac{\sin 56\tfrac{1}{4}^\circ}{\sin 33\tfrac{3}{4}^\circ} = \frac{\cdot 83}{\cdot 55}$$

$$\text{Dev.} = \frac{5\times\cdot 83}{\cdot 55} = \frac{\cdot 83}{\cdot 11} = 7\cdot 55^\circ \text{ W. (change name)}$$

$$(2)\ \frac{\text{new dev.}}{7\cdot 55} = \frac{\tan \text{dip } (-50^\circ)}{\tan \text{dip } (+70^\circ)} = \frac{1\cdot 19}{2\cdot 75} = \cdot 43$$

$$\text{Dev.} = 7\cdot 55\times\cdot 43 = 3\cdot 25^\circ \text{ E.} \quad \textit{Ans.}$$

Dev. changes name because dip has changed sign.

Example IV.

If $b = 4^\circ$ E. when heading E.S.E., dip -55°, required the direction of ship's head and the maximum value of b when the dev. from same cause was 3° W., dip $+66^\circ$.

$$\frac{\text{new dev.}}{\text{old dev.}} = \frac{\sin \text{new co.}\times\tan \text{new dip}}{\sin \text{old co.}\times\tan \text{old dip}}$$

$$\frac{3^\circ \text{ W.}}{4^\circ \text{ E.}} = \frac{\sin X^\circ \times \tan + 66^\circ}{\sin 67\tfrac{1}{2}^\circ\times\tan - 55^\circ}$$

$$\text{Sin. } X^\circ = \frac{3\times\cdot 923\times 1\cdot 43}{4\times 2\cdot 25} = \frac{3\cdot 96}{9} = \cdot 44$$

$$X^\circ = 26\tfrac{1}{2}^\circ$$

The dev. having changed from E. to W. and the sign of the dip having also changed, the ship's head must be still easterly, viz.

S. $26\tfrac{1}{2}^\circ$ E. or N. $26\tfrac{1}{2}^\circ$ E. *Ans.*

$$\text{Max. } b = \frac{b}{\sin \text{co}} = \frac{3}{\sin 26\tfrac{1}{2}^\circ} = \frac{3}{\cdot 44} = 6\cdot 8$$ due to vertical iron $\therefore$ induced B is $-6\cdot 8^\circ$. *Ans.*

Example V.

Given $B = +10^\circ$, $b = -4^\circ$, H.F. $= 1\cdot 2$, dip $= +60^\circ$.

Find deviation when heading West at a place where H.F. $= \cdot 9$, dip $= -72^\circ$

(1) Adjust sub-permanent B for change of H.F.

(2) Adjust induced b for change of dip.

$$(1)\ \frac{\text{new } B}{\text{old } B} = \frac{\text{old H.F.}}{\text{new H.F.}} = \frac{12}{9} = 1\cdot 33$$

$B = 10\times 1\cdot 33 = 13\cdot 3^\circ$ W. (West because $+B$ gives West deviation on westerly courses.)

(2) $\dfrac{\text{new } b}{\text{old } b} = \dfrac{\tan \text{new dip } (-72^\circ)}{\tan \text{old dip } (+60^\circ)} = \dfrac{3{\cdot}07}{1{\cdot}73} = 1{\cdot}77$

$b = 4 \times 1{\cdot}77 = 7{\cdot}1^\circ$ W. (West because the dip has changed sign thus converting the original $-b$ into a $+b$ giving West deviation on westerly courses.)

$B = 13{\cdot}3^\circ$ W.
$b = 7{\cdot}1^\circ$ W.

Total $B = \underline{\underline{20{\cdot}4}}$ W. = Dev. on West. *Ans.*

Example VI.

Head in building yard N. 50° W., dev. = 10° W. on N. 10° E. due to hard iron, dip = 70°.

Find deviation on S. 50° W., where dip = 50°.

Note that the neutral point is N. 50° W.

$$\frac{\text{Dev. on S. 50 W.}}{\text{Dev. on N. 10 E.}} = \frac{\text{sin angle from neutral pt. } (80^\circ)}{\text{sin angle from neutral pt. } (60^\circ)} = \frac{{\cdot}98}{{\cdot}87} = 1{\cdot}13$$

Dev. on S. 50° W. = $10^\circ \times 1{\cdot}13 = 11{\cdot}3^\circ$ E.

$$\frac{\text{new dev.}}{\text{old dev.}} = \frac{\text{cos. old dip } (70^\circ)}{\text{cos. new dip } (50^\circ)} = \frac{{\cdot}34}{{\cdot}64} = {\cdot}53$$

Dev. = $11{\cdot}3 \times {\cdot}53 = 5{\cdot}98^\circ$ E. *Ans.*

The dev. is East because neutral point is to the right of S. 50° W.

MISCELLANEOUS EXERCISES.

1. Given coefficient $C + 16^\circ$, and sub-permanent $B - 12^\circ$, find head as in building yard.

Ans. N. 53° E.

2. Head when building S. 40° E., $+C = 5^\circ$, H.F. 1·0, find deviation due to hard iron heading West and H.F. 1·5.

Ans. 4° W.

3. On magnetic equator, head East, dev. 10° W., H.F. 1·5, in a high North latitude H.F. 1·0, dip + 65°, dev. on East 19° W., find values of B and b.

Ans. $B - 15^\circ$, $b - 4^\circ$.

4. Heading S.S.E., dev. from hard iron 15° W., this being a maximum. If dev. on East is nil, find value of b.

Ans. $+5\cdot7$.

5. Given $B = +10°$, $C = -7°$, H.F. 1·2, find direction of head in building yard and deviation on N. 20° W. where H.F. $=\cdot9$.

Ans. S. 35° W.; 13·3° W.

6. Vessel built heading N. 50° E., deviation due to hard iron 13° W. on S. 70° E. Find values of coefficient B and C.

Ans. $B-9\cdot6°$, $C+11\cdot5°$.

7. Heading W.S.W., dip $-50°$, dev. 4° W. due to vertical iron. If the deviation from the same cause is 3° E. at a place where the dip is $+60°$, find how ship was heading and the maximum value of b at the latter place.

Ans. S. 28·5° W. or N. 28·5° W., b $+6\cdot25°$.

8. Heading north-easterly at right angles to building direction, the deviation due to hard iron was 17° E., and on North it was 5° E. Find head when building and value of sub-permanent B.

Ans. S. 17° E., $B = +16\cdot3°$.

9. Heading E.N.E., heeling 10° to starboard, error 10° W. Find heeling error when heading N.W. by W. and heeling 9° on starboard tack.

Ans. 12·9° E.

10. A magnet deflects a needle 10° when in the end-on position at a distance of 12 inches. Find deflection if placed broadside on at a distance of 10 inches.

Ans. 8·64°.

11. If an athwartship magnet corrects 10° when vessel is heading North, how much will it correct when heading N. 50° W.

Ans. 6·43°.

12. If the fore and aft magnet corrects 20° with ship heading East magnetic, how much will the same magnet correct when heading S. 30° W.?

Ans. 10°.

13. If the Flinders bar corrected $+8°$ with dip $+58°$, what values will it correct with dip $-70°$ and $+55°$?

Ans $-13\cdot7°$. $+7\cdot15°$.

14. When heeling 7° to starboard, the error was 11° W. on N. 30° E. Find the heeling error on S. 40° E. when heeled 5° to starboard.

Ans. 6·95° E.

15. Given head East, dev. 14° E., H.F. 0·9, dip 47°, at a place *A*. Later when on the magnetic equator H.F. 1·5, deviation on East was 6° E. How much deviation should have been corrected with a fore and aft magnet at position *A*?

Ans. 10° E.

16. A ship has no deviation from hard iron while heading E. by S. If deviation on North was 19° E., and on East was nil, find the maximum deviation due to induced *B*.

Ans. −3·8°.

17. Heading N.N.E., the deviation due to hard iron was 15° E., required the deviation due to the same cause when heading S.W. by W. if ship's head was E.S.E. in building yard.

Ans. 12·5° W.

18. Ship on magnetic equator heading East, dev. 8° E., heading N.E., Dev. 12° E. If coefficient *D* be properly compensated find the maximum deviation due to hard iron.

Ans. 12°.

130. Sub-permanent and Induced *B*.

It is possible in some branches of physical science to press rigid mathematical theory too far, and this may easily be done when dealing with the transient, fickle and unstable magnetism of a merchant ship. Change of trim, of cargo and of her magnetic character generally, the acquisition of superfluous magnetism by the iron correctors, also the weakening of the power of permanent magnets with the lapse of time, all conspire to upset the perfect working of the fundamental theory by vitiating the assumed factors on which the mathematical formulae depend. The surest and safest procedure is the practical one of finding the actual error of the compass, compensating it experimentally and verifying the result by observation. Where, however, a ship is kept in the same trim and not subjected to excessive concussion the effect of soft iron, as distin-

guished from that of permanent magnetism, in producing semi-circular deviation, may be closely estimated at a well placed compass. One example, which has a practical application to the correction of one of the ship's magnetic elements, namely the fore and aft force due to vertical iron, may illustrate the process of how physical phenomena may be expressed in mathematical language. Adopting the notation and symbols of the Admiralty Manual we have two equations:

$$\text{I.}\quad P + cZ_1 = \lambda\, H_1 B_1.$$
$$\text{II.}\quad P + cZ_2 = \lambda\, H_2 B_2.$$

P represents the fore and aft force of sub-permanent magnetism, producing that part of co-efficient B which is constant in all latitudes, so this factor may stand by itself.

c represents the force of the induced magnetism in vertical iron in the fore and aft line of the ship, producing induced B which varies as the tangent of the earth's dip. This factor depends on the earth's vertical force so it is associated in the equation with

Z_1 which represents the vertical force of the earth at a given place and

H_1 represents the horizontal force of the earth at the same place.

λ represents the horizontal directive force of the compass needle on board the ship.

B_1 represents the natural sine of the mean deviation found on east and west when the deviation is small, and as B depends on λ and H these three factors hang together in the equation.

Z_2, H_2, and B_2 represent, respectively, the vertical force, the horizontal force, and the natural sine of the deviation on east and west at a second place separated widely in latitude from the first place.

The deviation found with the ship's head on east and west is due to the combined action of P and c, the object of the equation being to separate c from P, and so to arrive at the amount of Flinders bar required to counteract c; the Flinders bar is also a force c but of an opposite sign to the ship's c. The values of Z_1, Z_2, H_1, and H_2 are given in Charts V. and III. of the Appendix, B_1, B_2 are found when the ship's head is east or west; λ may be taken as ·9 at a standard compass; P and c are the unknown quantities, but P disappears if we subtract equation II. from I. Let us try.

Subtract II. from I.

I. $P + cZ_1 = \lambda\, H_1 B_1.$

II. $P + cZ_2 = \lambda\, H_2 B_2.$

$$cZ_1 - cZ_2 = \lambda\, H_1 B_1 - \lambda\, H_2 B_2.$$

$$c(Z_1 - Z_2) = \lambda\,(H_1 B_1 - H_2 B_2).$$

$$c = \lambda\,\frac{(H_1\,B_1 - H_2\,B_2)}{Z_1 - Z_2}$$

EXAMPLE

At Perim the deviation on east was $+ 10°$; later at Falmouth it was $+6°$. Find the amount of deviation at each place caused by sub-permanent magnetism and by vertical iron.

	Perim.	Falmouth.
From Chart II.	Dip $= 5° \ (\theta_1)$	Dip $= 66° \ (\theta_2)$
„ III.	H.F. $= 1{\cdot}9 \ (H_1)$	H.F. $= 1{\cdot}0 \ (H_2)$
	V.F. $= 1{\cdot}9 \tan 5° \ (Z_1)$	V.F. $= 1 \tan 66° \ (Z_2)$
	$Z_1 = {\cdot}16625$	$Z_2 = 2{\cdot}246$

B_1=nat. sine $10° = {\cdot}1736$ B_2= nat. sine $6° = {\cdot}1045$

$$c = \frac{H_1\,B_1 - H_2\,B_2}{Z_1 - Z_2} \text{ neglecting lambda.}$$

$$\text{Nat. sine } c = \frac{1{\cdot}9 \times {\cdot}1736 - 1 \times {\cdot}1045}{{\cdot}16625 - 2{\cdot}246}$$

$$\text{Nat. sine } c = \frac{{\cdot}22534}{2{\cdot}07975} = -{\cdot}1083 \therefore c = -6{\cdot}2°$$

At Perim.		*At Falmouth.*	
Induced B	$=$ c. tan dip.	Induced B	$=$ c. tan. dip.
„	$= -$ 6·2 tan. 5°	„	$= -$ 6·2 tan. 66°
„	$= -$ 6·2 × ·0875	„	$= -$ 6·2 × 2·246
Induced B	$= -$ ·5	Induced B	$= -$ 13·92
Total B	$= +$ 10·0	Total B	$= +$ 6
Sub.-per. B	$= +$10·5	Sub.-per. B	$= +$ 19·92

The problem may be solved as an ordinary algebraic equation, but this method requires the investigation to be made for every new condition, whereas, the stock formula previously established applies to all cases, by simply putting in the values for B, H and Z. Perhaps, however, the solution as an equation is less involved.

The deviation appearing on east is co-efficient B made up of two parts, one arising from sub-permanent magnetism and the other from induced magnetism in vertical iron. Let us call the two parts big B and little b. It is obvious from the Perim-Falmouth question that the vertical iron is an attraction towards the stem because the total attraction towards the bow has diminished in the higher magnetic latitude, so that $B_1+b_1=+10°$ at Perim; and $B_2+b_2=+6°$ at Falmouth. We have therefore to get values for B_1 and b_1 in terms of B_2 and b_2 respectively, then evolve a suitable equation to get values for B_2 and b_2.

$$\frac{B_1}{B_2}=\frac{\text{H.F. at Falmouth } (H_2)}{\text{H.F. at Perim } (H_1)}$$

$$\therefore\ B_1=\frac{B_2\,H_2}{H_1}=\frac{B_2}{1.9}\quad\ldots\ldots\ldots\ldots\ \text{I}$$

$$\text{and }\frac{b_1}{b_2}=\frac{\text{tan. dip at Perim } (\theta_1)}{\text{tan. dip at Falmouth } (\theta_2)}$$

$$\therefore\ b_1=\frac{\tan.\ 5°}{\tan\ 66°}\times b_2=\frac{\cdot 0875}{2\cdot 246}\,b_2\quad\ldots\ldots\ \text{II}$$

Given the dev. on east at Perim, $B_1+b_1=+10°$

substitute values in Eq. I and II $\dfrac{B_2}{1\cdot 9}+\dfrac{\cdot 0875}{2\cdot 246}\,b_2=+10°$

Multiply throughout by 1·9 $B_2+\cdot 07\ b_2=19°$

but dev. on east at Falmouth $B_2+\ \ b_2=\ 6°$

by subtraction $\cdot 93\ b_2=-13°$

from which $b_2=-14°$

but $B_2+b_2=6°$ or $B_2+(-14)=6$

$\therefore\ B_2=14+6=20°$.

At Falmouth

Dev. due to hard iron $(B_2)=20°$ E.

Dev. due to soft iron $(b_2)=14°$ W.

At Perim

$$B_1=\frac{B_2}{1\cdot 9}=\frac{20}{1\cdot 9}=+10.5°$$

$$b_1=\frac{\cdot 0875}{2\cdot 246}\,b_2=\frac{\cdot 0875}{2\cdot 246}\times-14=-\cdot 5$$

Dev. due to hard iron $(B_1)=10\cdot 5°$ E.

Dev due to soft iron $(b_1)=0\cdot 5$ W.

Example

At New York, H.F. = 1. Dev. on east = 0°. Dip = 72°. At Buenos Aires H.F. = 1·4. Dev. on east = 15° W. Dip = 38°. Find the deviation due to hard iron and soft iron at both places.

At New York $B_1+b_1=0$
At Buenos Aires $B_2+b_2= -15°$

$$\frac{B_1}{B_2}=\frac{\text{H.F. at Buenos Aires}}{\text{H.F. at New York}}=\frac{1·4}{1} \quad \therefore B_1 = 1·4B_2 \quad . \quad . \quad . \quad \text{I}$$

$$\frac{b_1}{b_2}=\frac{\text{tan. dip. New York } 72°}{\text{tan. dip. B. Aires } 38°}=\frac{3·078}{-·781}=-3·941$$

$$\therefore b_1 = -3·941\ b_2 \quad . \quad . \quad . \quad . \quad \text{II}$$

the sign of b_2 is changed being in the opposite hemisphere.

given . . . . $B_1+b_1=0$
substituting values as in Eq. I and II $1·4\ B_2-3·941\ b_2=0$
given $B_2+b_2= -15$, multiply by 1·4, $1·4\ B_2+1·4\ b_2=-21$
by subtraction, $-5·341\ b_2= 21$
$\therefore$ $b_2 = -\ 3·932$
but . $B_2+b_2 = -15$
by subtraction $B_2 = -11·068$

At Buenos Aires

Dev. due to hard iron (B_2)=11·068 W.
Dev. due to soft iron (b_2)= 3·932 W.

At New York

$B_1 =1·4B_2 \quad = +1·4 \times -11·068 = -15·495$
$b_1 = -3·941b_2 \quad = -3·941 \times -3·932 = +15·495$
$\therefore$ Dev. due to hard iron (B_1) =15·495° W.
Dev. due to soft iron (b_1) =15·495 E.

Exercises.

(1) At Greenock the deviation on east = +8°; at Demerara the deviation on east = +6°. Find how much of it is due to sub-permanent magnetism and to vertical iron.

Greenock dip = 70°. H.F. = 0·9. V.F. = 2·5
Demerara dip = 25°. H.F. = 1·6 V.F. = 0·75
Nat. sine 8° = ·139. Nat. sine. 6° = ·104.

(2) At Bangkok where the H.F. $= 2\cdot1$ and dip $= 10°$, the deviation on east was $+8°$, and on west $-10°$. At Glasgow the H.F. $=0\cdot9$ and dip $=71°$, the deviation on east is $+6°$, and on west $-4°$. Find how much of the deviation is due to hard iron and soft iron at both places.

ANSWERS.

(1) Greenock.	Induced B	$= - 3\cdot8°$	Sub-permanent B	$= +11\cdot8°$
Demerara.	,,	$= - 0\cdot6$,	,,	$= + 6\cdot6$
(2) Bangkok.	Soft iron	$= - 1\cdot1$	Hard iron	$= +10\cdot1$
Glasgow.	,,	$= -18\cdot3$	,,	$= +23\cdot3$

131. Hard and Soft Iron and Head in Building Yard.

EXAMPLE

At Newcastle the deviation on east was $+9°$; on north it was $+12°$; dip $= 70°$. At Shanghai the deviation on east is $+5\cdot2°$; and on north $+6\cdot4°$; dip $= 48°$. Find the direction of ship's head when she was being built.

It is necessary, in order to find the direction of the ship's head in the building yard, to know the values of co-efficients B and C due to sub-permanent magnetism. The deviation on north may be taken as due to hard iron only, but the deviation on east is caused by both hard iron and soft vertical iron, and so we are involved in the mathematical complication of separating big B from little b with the minimum of information given in the question.

At Newcastle

Let B_1 represent the dev. on east due to hard iron,
and b_1 represent the dev. on east due to soft iron,
then (B_1+b_1)=total dev. on east $= +\ 9°$
and C_1 = ,, on north $= +12°$
Dip $=70°$. Nat. tan. $70°=2\cdot75$ (θ_1)

At Shanghai

Let (B_2+b_2)=total dev. on east $= +5\cdot2°$
and C_2 = ,, on north $= +6\cdot4°$
Dip $= 48°$. Nat. tan. $48° = 1\cdot11$ (θ_2)

B and C due to hard iron vary inversely as the earth's horizontal force and consequently they maintain the same ratio to each other, and we may write—

$$\frac{B_1}{B_2}=\frac{C_1}{C_2}=\frac{\text{dev. on north at Newcastle}}{\text{dev. on north at Shanghai}}=\frac{120}{64}=\frac{15}{8}$$

$$\therefore\ B_1=\frac{15}{8}B_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{I}$$

The part of B due to soft iron (b_1) varies as the tangent of the dip, therefore $\frac{b_1}{b_2}=\frac{\theta_1}{\theta_2}\ \therefore\ b_1=\frac{2\cdot75}{1\cdot11}b_2$ II

But we are given $\qquad B_1+b_1=+9^\circ$

substitute values in Eq. I and II $\frac{15}{8}B_2+\frac{2\cdot75}{1\cdot11}b_2=+9$

divide throughout by $\frac{15}{8}$ $\qquad B_2+1\cdot323\,b_2=4\cdot8$

$$\begin{array}{lrl}
\text{but} & B_2+\ b_2 & =5\cdot2 \\ \hline
\text{by subtraction} & \cdot323\ b_2 & =-\cdot4 \\
\therefore & b_2 & =-1\cdot24
\end{array}$$

$$\begin{aligned}
\text{given}\quad B_2+b_2 &=5\cdot2\\
B_2-1\cdot24 &=5\cdot2\\
\therefore\ B_2 &=6\cdot44
\end{aligned}$$

At Shanghai

Sub-permanent $B=+6\cdot44^\circ$ and $C=+6\cdot4^\circ$

Nat. tan. head in building yard $=\frac{+C_2}{+B_2}=\frac{6\cdot4}{6\cdot44}=1\cdot006$

$\therefore$ Head was S. 45° E. when building.

At Newcastle

$$B_1=\frac{15}{8}B_2=\frac{15}{8}\times6\cdot44=12\cdot07^\circ$$

Sub-permanent $B=+12\cdot07^\circ$, and $C=+12^\circ$

Nat. tan head in building yard $=\frac{+C_1}{+B_1}=\frac{12}{12\cdot07}=1\cdot0059$

$\therefore$ Head was S. 45° E. when building.

EXERCISES.

(1) At San Francisco the deviation on east $=+8^\circ$; on north $=+7^\circ$; dip $=65^\circ$. At Calcutta the deviation on east $=+16\cdot03^\circ$; on north $=+10^\circ$; dip $=30^\circ$. Find direction of ship's head in building yard.

(2) At Aden the deviation on east = — 13°; on north = — 8°; dip = 5°. At Malta the deviation on east = — 15·3°; on north = — 10·9°; dip = 50°. Find direction of the ship's head in building yard.

ANSWERS.

(1) San Francisco, sub-permanent $B = +12°$, induced $B = -4°$
Calcutta, ,, $B = +17·1°$,, $B = -1·07°$
Head in building yard S. 30° 19′ E.

(2) Aden, sub-permanent $B = -13·2°$ Induced $B = +0·2°$
Malta ,, $B = -18·0°$,, $B = +2·7°$
Head in building yard N. 31° 12′ W.

TIME AZIMUTH.

132. The true bearing of the sun, or other celestial body, may be got from Azimuth Tables, the arguments required being the hour angle and declination of the body observed, and the latitude of the place.

An hour angle is the angle at the pole contained between the observer's meridian and the meridian of the body. It is usually expressed in hours, minutes, and seconds.

The hour angle of the sun is easily got from the apparent civil time at place, thus 9h. a.m. = 3h. east of the meridian; 10h. 30m. a.m. = 1h. 30m. east. But 3h. p.m. = 3h. west of the meridian, and 1h 30m. p.m. = 1h. 30m. west.

The most popular Tables are those specially arranged for sun azimuths, in which the apparent time at ship is given instead of the hour angle. (*See* Appendix.) Table IV. which gives the azimuths of the sun for latitude 56° as taken from *Brown's Completed Burdwood Azimuth Tables.*

To find the West Hour Angle at Ship.—H.A. at ship = G.M.T. + E + E. Long. or − W. Long. To the G.M.T. by chronometer add the quantity E, as taken from the *Nautical Almanac* for the date and time of question, to get the H.A. at Greenwich; then apply the longitude in time (E. Long. add, W. Long. subtract) to convert the H.A. Greenwich into H.A. at ship. The Azimuth Tables are entered in the apparent time p.m. column with the west hour angle when it is less than 12 hours, but when the W.H.A. exceeds 12h. subtract 12h. from it, to give the apparent time with which the a.m. column is entered.

When entering the Azimuth Tables with the arguments, apparent time ship, latitude and declination, due regard must be paid to the precepts regarding the lat. and dec. being of the same, or of contrary, name, and whether the time is a.m. or p.m. The rule for naming the azimuth is given at the bottom of each page, and is named N. or S. in accordance with the latitude, E. when the time is a.m., W. when p.m.

Example

April 4th, p.m., off Greenock, lat. 55° 56′ N., long. 4° 45′ W., the Greenwich mean time was 4d. 16h. 30m. 00s., and the compass bearing of the sun N. 75° W. Find the sun's true bearing, thence the error of the compass, also the deviation for the ship's head at the

time, the variation from Chart I. being 18° W. *Nautical Almanac* elements: Dec. 5° 33′ N.; Eq. Time—3m. 9s. or *E* 11h. 56m. 51s.

	d.	h.	m.	s.
G.M.T. by chron., Apr.	4	16	30	00
E	+	11	56	51
H.A. Greenwich		4	26	51
Long. in time (W. subt.)		—	19	0
H.A. ship		4	7	51

Long. 4° 45′ W.
4
60)19 00
0h. 19m. 0s.

Enter Tables with:—

A.T. ship 4h. 8m. p.m.
Lat. 56° N.
Dec. $5\frac{1}{2}$° N.

True Az. N.	110°	50′	W.	
Comp. Az. N.	75	00	W.	
Comp. Error	35	50	W.	(named W. because the true az. lies to the left of the comp. az.)
Var.	18	00	W.	
Dev.	17	50	W.	(named W. because error lies to left of var. when laid off towards the N. point)

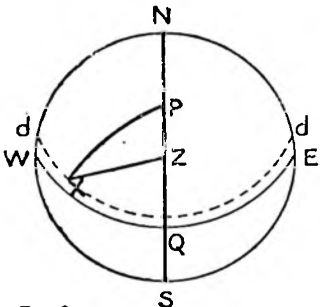


FIG. 81.

N E S W = horizon
P = pole
Z = zenith
W Q E = equinoctial
d d = sun's diurnal path
X = position of the sun

In triangle *P Z X*,
given *P Z* = co-latitude
P X = polar distance
$\angle P$ = hour angle

Find $\angle PZX$, the true azimuth.

Formula—

$$\tan.\ \tfrac{1}{2}\,(Z+X)=\frac{\cos.\ \frac{1}{2}\,(PZ\sim PX)}{\cos.\ \frac{1}{2}\,(PZ+PX)}\cot.\ \frac{P}{2}$$

$$\tan.\ \tfrac{1}{2}\,(Z\sim X)=\frac{\sin.\ \frac{1}{2}\,(PZ\sim PX)}{\sin.\ \frac{1}{2}\,(PZ+PX)}\cot.\ \frac{P}{2}$$

then $\frac{1}{2}\,(Z+X)+\frac{1}{2}\,(Z\sim X)=\angle PZX$, the azimuth of *X*.

From this formula the sun's true bearing has been computed for successive degrees of latitude and declination and for every fourth minute of time, and tabulated in *Burdwood's* and *Davis's Azimuth Tables*.

EXAMPLE XII.

February 4th, a.m. at ship, in lat. 56° N., long. 35° W., Greenwich mean time 4d. 11h. 40m. 22s., sun bore by compass S. 43° E., variation from Chart I. 35° W. Find the sun's true azimuth from the Tables, and thence the deviation for the ship's head at the time. *Nautical Almanac* elements: Dec. 16° 6′ S.; Eq. Time—14m. 6s. or *E* 11h. 45m. 54s.

			d.	h.	m.	s.
Long. 35° W.		G.M.T. Feb.	4	11	40	20
4		*E*		11	45	54
60)140						
2h. 20m.		H.A. Greenwich		23	26	14
	Long. in	time (W. subt.)		2	20	0
		H.A. ship		21	6	14
		Subtract		12		
		A.T. ship		9	6	14

Enter Tables with:—

A.T. ship 9h. 6m. a.m.	True Az. N. 137° 53′ E.		
Lat. 56° N.	Comp. Az. N. 137 00 E.		(Subtract the comp. bearing from 180° to name it from the N. point.
Dec. 16° S.			
	Error	0 53 E.	(named E. because the true bearing lies to the right of the comp. bearing.
	Var.	35 00 W.	
	Dev.	35 53 E.	(named E. because the error lies to right of the var. when laid off towards the N. point.

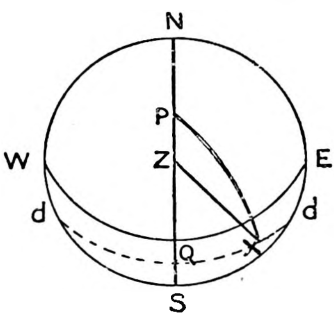


FIG. 82.

N E S W =horizon
P =pole
Z =zenith
W Q E =equinoctial
d d =sun's diurnal path
N Z S =observer's meridian
X =sun

In triangle *P Z X*,
given *P Z* =co-latitude
P X =polar distance
∠ *P* =hour angle
Find *P Z X* =true azimuth

TIME AZIMUTHS.

Given the following information, find from the Azimuth Table the true bearing of the sun, also the deviation of the compass for the direction in which the ship was heading at the time.

Exercise.	Apparent Time at Ship.	Lat.	Dec.	Bearing of Sun by Compass.	Var.
	h. m.				
1	3·24 p.m.	56° N.	20° N.	S. 70° W.	15° W.
2	8·40 a.m.	56° N.	10° S.	S. 37° E.	5° E.
3	9·26 a.m.	56° S.	16° S.	N. 47° E.	11° W.
4	2·30 p.m.	56° N.	5° S.	S. 60° W.	12° E.
5	4·10 p.m.	56° N.	18° N.	S. 72° W.	10° E.
6	10·6 a.m.	56° S.	12° N.	N. 30° E.	12° E.

Exercise

June 15th, a.m. at ship, in lat. 56° S., long. 20° E., time by chronometer 15d. 8h. 10m. 35s., which was fast 5m. 18s. on Greenwich mean time. Find the sun's true azimuth, and if the sun bore by compass N. 45° E., the variation being 5° W., find the deviation for the ship's head. *Nautical Almanac* elements: Dec. 23° 17′ N., Eq. Time—0m. 4s. from mean time, or *E* 11h. 59m. 56s.

Exercise

December 25th, in lat. 56° S., long. 60° W., Greenwich mean time 25d. 13h. 20m. 30s., the sun's bearing by compass, N. 63° E. Find the sun's true azimuth from the tables, also the deviation for the ship's course, the variation for the ship's position on Chart I. being 15° E. *Nautical Almanac* elements: Dec. 23° 25′ S., Eq., Time+0m. 5s. to mean time or *E* 12h. 0m. 5s.

Exercise

November 17th, p.m. at ship, in lat 56° N., long. 5° E., Greenwich mean time 17d. 15h. 10m. 00s., compass bearing of sun S. 45° W., var. 14° W. Find the sun's true azimuth thence the deviation for the ship's head. *Nautical Almanac* elements: Dec. 18° 54′ S., Eq. Time+15m. 2s. to mean time or *E* 12h. 15m. 2s.

Exercise

August 19th, a.m. at ship, in lat. 56° N., long. 50° W., Greenwich mean time 14h. 18m. 30s., the sun bore by compass south, var. 43° W. Find the true azimuth of the sun from the tables, and thence the deviation for the direction of the ship's head. *Nautical Almanac* elements: Dec. 12° 56′ N., Eq. Time—3m. 39s. from mean time or *E* 11h. 56m. 21s.

Answers to Time Azimuths.

Exercise.	True bearing.	Deviation.	Exercise.	True bearing.	Deviation.
1	N. 112° 17′ W.	12° 43′ E.	6	S. 150° 36′ E.	12° 36′ W.
2	N. 129° 29′ E.	18° 31′ W.	vii	S. 144° 47′ E.	4° 47′ W.
3	S. 128° 7′ E.	15° 53′ E.	viii	S. 121° 25′ E.	19° 25′ W.
4	N. 139° 16′ W.	31° 16′ W.	ix	N. 128° 8′ W.	20° 52′ E.
5	N. 102° 47′ W.	4° 47′ W.	x	N. 157° 24′ E.	20° 24′ E.

True Azimuth of a Star.—The true bearing of any star whose declination does not exceed that of the sun may be got from the Time Azimuth Tables by entering with the star's hour angle in the p.m. column.

The hour angle of a star is the difference between its right ascension and the right ascension of the meridian, the latter being found by adding together the mean time at ship and the quantity *R* from the *Nautical Almanac.*

$$* \text{ hour angle} = \text{S.M.T.} + R \sim * \text{ R.A.}$$

The star is east of the meridian when its R.A. is greater than the R.A.M., and west when less than the R.A.M.

Example

October 17th, p.m. at ship, in lat. 56° N., long. 15° W., the G.M.T. by chronometer 22h. 30m. 00s. Find the true azimuth of *α Tauri* (*Aldebaran*), also the deviation of the compass for the ship's head, the compass bearing of the star being S. 61° E. and the variation 26° W. *Nautical Almanac* elements: *R* 1h. 42m. 26s.; * R.A. 4h. 31m. 13s.; *Dec. 16° 21′ N.

	d.	h.	m.	s.	
G.M.T.	17	22	30	00	
Long.		1	0	0	W.
M.T. ship	17	21	30	00	
R	+	1	42	26	
R.A.M.		23	12	26	
* R.A.		4	31	13	(add 24 hours if required.)
* E.H.A.		5	18	47	(* E. because *R.A. 28½ hours is greater than R.A.M.)

Enter Tables with:—

			°	′	
* H.A. 5h. 18m. in p.m. column; Lat. 56° N.; Dec. 16½° N.	True Az.	N.	89	9	E.
	Comp. Bg.	N.	119	0	E.
	Error		29	51	W.
	Var.		26	00	W.
	Dev.		3	51	W

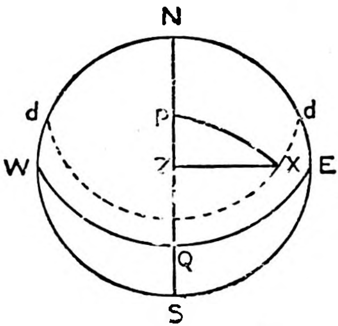


Fig. 83.

Example

In lat. 56° S., long. 75° 30′ W., G.M.T. March 4d. 21h. 10m. 30s. find the true azimuth of *a Pegasi* (*Markab*), and if the star bore N. 85° W. by compass and the variation is 22° E., find the deviation

for the ship's head at the time. *Nautical Almanac*: *R* 10h. 47m. 15s.; * R.A. 23h. 0m. 41s.; * Dec. 14° 46′ N.

	d.	h.	m.	s.	
G.M.T.	4	21	10	30	
Long. W.	−	5	2	00	
M.T. ship	4	16	8	30	
R	+	10	47	15	
R.A.M.		2	55	45	(add 24 hours if required)
* R.A.		23	0	41	
* W.H.A.		3	55	04	(* W. because * R.A. 23h. is less than R.A.M. 26h. 55m.)

Enter Tables with:—

* H.A. 3h. 55m. in p.m. column
Lat. 56° S.
Dec. 15° N.

True Az.	S.	124°	9′	W.
Comp. Bg.	S.	95	0	W.
Error		29	9	E.
Var.		22	0	E.
Dev.		7	9	E.

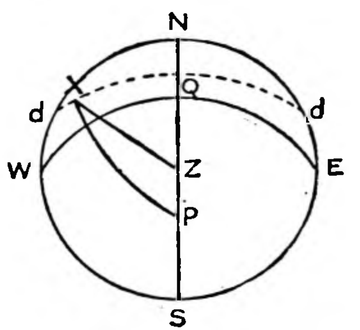


FIG. 84.

The stars in the most favourable position for azimuth observations are those situated between 10° and 30° altitude. Table II. Appendix is arranged to facilitate the selection of the most suitable of such stars for determining the error of the compass, it is really

Table IV. from *Practical Information on the Deviation of the Compass*, by Captain J. T. Towson, F.R.G.S., which we have been allowed to insert here by kind permission of the publishers, Messrs. J. D. Potter, 145 Minories, London.

The table is arranged for both hemispheres, and is entered at the side with the latitude, and at the top with the R.A.M., or sidereal time of observation, which is another name for the same quantity. The corresponding numbers refer to the names of the stars, those bearing east of the meridian being given above the line, and the west stars below it.

In Example XIII. the R.A.M.=23 hours, lat. 56° N.; with these arguments enter Table II. and the numbers given are $\frac{1,\ 2,\ 4,\ 7,\ \text{E.}}{8,\ 11\ \text{W.}}$ the stars corresponding to these numbers in the table of reference being *Aldebaran*, *Capella*, *Castor* and *a Ursae Majoris*, east of the meridian, γ *Ursae Majoris* and *Altair*, W. of the meridian.

Similarly in Example XIV., the R.A.M.=3 hours, lat. 56° S., the figures are $\frac{21,\ 19,\ 3,\ 1,\ 16\ \text{E.}}{24\ \ \text{W.}}$ the stars being α *Centauri*, α *Crucis*, α *Orionis*, *Aldebaran*, *Sirius*, east of the meridian, but only α *Pavonis* west of the meridian.

Exercise I

June 15th, in lat. 56° N., long. 9° W., the Greenwich mean time being 15d. 2h. 20m. 00s., give the names of the stars most favourably situated for azimuth. Find the true azimuth of *Arcturus* from the Time Azimuth Tables, and if it bore N. 62° W. by compass, the variation being 20° W., find also the deviation for the ship's head. *Nautical Almanac* elements—*R* 17h. 34m. 21s.; * R.A. 14h. 11m. 58s., *Dec. 19° 36′ N.

Exercise II.

December 4th, 19h. 35m. 30s., Greenwich mean time, in lat. 56° N., long., 6° E., give the names of the stars most reliable for finding the error of the compass. Find the true azimuth of *Aldebaran*, also the deviation for ship's head, the compass bearing being S. 55° E., and the variation 13° W. *Nautical Almanac* elements—*R* 4h. 51m. 12s.: * R.A. 4h. 31m. 18s., * Dec. 16° 21′ N.

ANSWERS.

Exercise I.

(1) *Capella* and *Markab*, E.; *Arcturus*, α *Ursae Majoris* and γ *Ursae Majoris*, W.; *Arcturus*, W.H.A. 5h. 6m. 13s.; true azimuth N. 89° 45′ W., deviation 7° 45′ W.

(2) *Castor*, α *Orionis*, α *Ursae Majoris*, *Aldebaran*, E., *Vega*, *Altair*, W.; *Aldebaran*, E.H.A. 3h. 40m. 36s.; true azimuth N. 110° 43′ E., deviation 1° 17′ W.

Examination Paper I.

133.—(1) Given coefficient $B = -12°$, coefficient $C = -6°$, find the direction of the ship's head whilst building.

(2) Given ship's head during construction S.S.W., coefficient $C = -10°$, find coefficient B.

(3) When on starboard tack, heading S.S.E. and heeling 15°, the error was +12°, find the error for W.N.W., and heeling 10° on the port tack.

(4) From the following deviations, determine the coefficients A, B, C, D and E, and construct a Table of Deviations for each point of the compass from N.N.E. to S.S.W. by way of West.

Deviation at	N.	(6° E.)	S.	(1° W.)
	N.E.	(11° W.)	S.W.	(8° E.)
	E.	(26° W.)	W.	(21° E.)
	S.E.	(18° W.)	N.W.	(21° E.)

(5) August 25th at 2h. 50m. a.m., mean time at ship, in lat. 50° N., long. 45° 30′ W., what stars would be in a good position for determining the error of the compass? *Nautical Almanac* elements—R.A.M.S. 10h. 10m. 45s. or R 22h. 10m. 45s.

(6) June 28th, p.m. at ship, in lat. 56° 15′ N., long. 35° 15′ W., a chronometer correct on G.M.T. showed 17h. 30m. 20s. Find the sun's true bearing and if the sun bore by compass N. 84° W., the variation being 37° W., find the deviation for the ship's head at the time. *Nautical Almanac* elements—Dec. 23° 18′ N., Eq. Time —2m. 55s. or E 11h. 57m. 05s.

(7) March 17th, a.m. at ship, in lat. 56° N., long. 5° E., G.M.T. 17d. 2h. 30m. 00s., find the true azimuth of α *Leonis*

(*Regulus*) also the deviation for the ship's head, the compass bearing being S. 72° W., and variation 14° W. *Nautical Almanac* elements—*R* 11h. 39m. 22s.; *R.A. 10h. 4m. 0s.; *Dec. 12° 22′ N.

(8) A magnet when "side on" at a distance of 22 inches from a needle deflects it 6°, how many degrees would it be deflected when the magnet is 12 inches from the needle and placed "end on" to it?

(9) The average time occupied by a horizontal needle in making 10 vibrations on shore was 60 seconds, and at the binnacle on board 64 seconds, the deviation for the ship's head being 22°. Find co-efficient λ (lambda).

(10) At Liverpool co-efficient *B* due to hard iron was + 10° and co-efficient *C* +14°. Find the values of *B* and *C* at Perim.

(11) The deviation due to vertical soft iron was +5° at New York, what would be its value at Calcutta and Sydney, Australia?

(12) There is no deviation from hard iron on an uncompensated compass when heading N.E., deviation on east = −15°, on south = −12°. Find the value of induced *B*.

(13) Given deviation on south = +12°, on west = +7°, on S. 22 W. = + 15°. Find the deviation on S. 67° E.

(14) At Rio de Janeiro the deviation on north = +12°, on east = −12°, on N.E. = +7°, on S.W. = −1°; H.F. = 1·35 dip. = 15°. Find the deviation on N. 50° W. at Montreal where the H.F. = ·8, and dip = 75°.

(15) At Buenos Aires the deviation on east = +14°, on west = −10°; dip = −35°; H.F. = 1·38; V.F. = −·96.

At Gibraltar the deviation on east = +4°, on west = −6°; dip = 55°; H.F. = 1·3; V.F. = 1·85. How much deviation at each place was caused by sub-permanent magnetism and by vertical iron?

(16) At Durban the deviation on east = −13°, on north = −12°, dip = 60°. At Rio de Janeiro the deviation on east = −8·86°, on north = −10·15°, dip = 13°. Find direction of ship's head in building yard.

ANSWERS.

(1) N. 27° W.
(2) *B* = + 24.
(3) Error + 3½°.

(4) $A=0°$, $B=-23\frac{1}{2}°$, $C=+3\frac{1}{2}°$, $D=-1\frac{1}{2}°$, $E=+2\frac{1}{2}°$. Deviation 5° 6′ W., 0° 30′ E., 6° 0′ E., 10° 54′ E., 15° 6′ E., 18° 24′ E., 20° 36′ E., 21° 48′ E., 22° 18′ E., 22° 00′ E., 21° 0′ E., 19° 24′ E., 17° 30′ E., 15° 12′ E., 12° 36′ E., 9° 48′ E., 6° 30′ E.

(5) *Castor, a Orionis, a Ursae Majoris*, E. of meridian. *Vega, Altair*, W. of meridian.

(6) True azimuth N. 114° 40′ W., deviation 6° 20′ E.

(7) True azimuth N. 102° 48′ W., deviation 19° 12′ E., *W.H.A. 4h. 25m. 22s.

(8) 73·8°.

(9) $\lambda = \cdot 828$.

(10) $B+5°$, $C+7°$.

(11) Calcutta, dip 30°, deviation $+1°$; Sydney, dip 60°, deviation $-3{\cdot}2°$.

(12) Sub-permanent $B=-12°$, induced $B=-3°$.

(13) Dev. on S. 22° W. due to B and $C=+13{\cdot}75°$, and to horizontal iron $+1{\cdot}25°$; co-eff. $D=+1{\cdot}8°$; dev. on S. 67° E. $=-3{\cdot}11°$.

(14) At Rio, dev. from hard iron $=+16{\cdot}9°$, and from horizontal iron $=-2{\cdot}95°$. At Montreal, dev. from hard iron $=+28{\cdot}5°$, and from horizontal iron $=-2{\cdot}95°$, dev. on N. 50° W. $=+25{\cdot}55°$.

(15) $c=-{\cdot}0593$. At Buenos Aires, induced $B=+2{\cdot}3°$, sub-permanent $B=+9{\cdot}7°$. At Gibraltar, induced $B=-4{\cdot}8°$, sub-permanent $B=+9{\cdot}8°$.

(16) Durban. Sub-permanent $B=-9{\cdot}9°$, induced $B=-3°$, $C=-12°$.

Rio. Sub-permanent $B=-8{\cdot}46°$, induced $B=-{\cdot}4°$, $C=-10{\cdot}15°$. Head N. 50° 12′ W.

Examination Paper II.

(1) Given co-efficient $C=+10°$, ship's head in the building yard was S.E., find co-efficient B.

(2) Given co-efficient $B=+15°$, and $C=-10°$, find how the ship's head was when being built.

(3) Heading N.E. by E., heeling 10° to port, the error was $+8°$, what would the heeling error be when heading N.N.W. and heeling 18° to starboard?

(4) Given the following deviations, compute the co-efficients A, B, C, D and E, then construct a deviation table for every second point of the compass.

Deviation on	N.	(3° E.)	S.	(1° E.)
	N.E.	(15° E.)	S.W.	(16° W.)
	E.	(29° E.)	W.	(28° W.)
	S.E.	(14° E.)	N.W.	(18° W.)

(5) July 20th, at 8 p.m. mean time at ship in lat. 56° S., long. 30° E., what stars are in a good position for azimuth observations. *Nautical Almanac* elements—*R* 19h. 50m. 48s.

(6) Feb. 4th, a.m. at ship in lat. 56° N., long. 6° 10′ W., the G.M.T. by chron. was 10h. 18m. 0s., the compass bearing of the sun was S. 12° E., and the variation 19° W. Find the sun's true azimuth, also the deviation of the compass. *Nautical Almanac* elements—Dec. 16° 24·2′ S.; Eq. Time—14m. 1s., *E* 11h. 45m. 59s.

(7) Dec. 25th, in lat. 56° N., long. 35° 30′ W., G.M.T. 25d. 10h. 20m. 0s. (*a*) *Orionis* (*Betelgeuse*) bore by compass S. 50° E., and if the variation was 37° W., find the deviation for the ship's head. *Nautical Almanac* elements—*R* 6h. 14m. 27s.; *R.A. 5h. 50m. 50s.; *Dec. 7° 23·6′ N.

(8) Co-efficient $B=15°$, a fore and aft magnet corrects 8° of this deviation when 20 inches from the compass, how far should it be placed from the compass in order to correct the whole of *B*?

(9) Two places on board ship, *A* and *B*, were equally convenient as a position for the standard compass. To make *x* vibrations on shore a horizontal needle occupied 52 seconds, at *A* 56 seconds, at *B* 62 seconds, compare the directive force at *A* and *B*, and state which would be the more suitable for the compass.

(10) At Melbourne the semi-circular deviation due to hard iron was +12°, what would it be at Singapore?

(11) At Gibraltar the value of induced *B*, head east, was +3°, what would be its value when heading W.N.W. at Devonport?

(12) There is no deviation from hard iron on an uncompensated compass when heading E. by S., dev. on north = + 18·5°, on east = 0°. Find induced *B*.

(13) Given deviation on north = 21° E., on west = 21° W., on S. 56° E. = +7·1°. Find deviation on S. 22° E.

(14) At Melbourne the deviation on north = −15°, on east = −6°, on N.E. = −15°, on S.W. = +18°; H.F. = 1·3. dip = 68°. Find the deviation on N. 30° W. at Singapore where the H.F. = 2·1 and dip = 15°.

(15) At Melbourne the deviation on east = −8°, dip = −68°; H.F. 1·3; V.F. = −3·22. At Singapore the deviation on east = −4°,

dip=15°; H.F.=2·1; V.F.=·563. How much of the deviation at each place is due to sub-permanent magnetism and vertical iron?

(16) At Port Said the deviation on east=−13°, on north=+10°, dip=40°. At New York the deviation on east=−15¼°, on north =+14½°; dip=70°. Find direction of ship's head when being built.

ANSWERS.

(1) $B=+10$.

(2) S. 34° W.

(3) −23·7°.

(4) $A+1\frac{1}{4}°$, $B+28\frac{1}{2}°$, $C+1°$, $D+\frac{3}{4}°$, $E+\frac{3}{4}°$; deviations—3° 0′ E., 14° 0′ E., 22° 48′ E., 28° 0′ E., 29° 0′ E., 26° 6′ E., 19° 54′ E., 11° 12′ E., 1° 0′ E., 9° 30′ W., 18° 48′ W., 25° 30′ W., 28° 0′ W., 25° 42′ W., 18° 48′ W., 8° 48′ W., 3° 0′ E.

(5) *Achernar* and *Altair*, E. of meridian, *Arcturus*, *Canopus*, and *Spica*, W. of meridian.

(6) True azimuth N. 145° 36′ E.; deviation 3° 24′ W.

(7) True azimuth N. 116° 36′ E.; deviation 23° 36′ E.; *E.H.A. 3h. 38m. 23s.

(8) 16·2 inches.

(9) $A=·86$, $B=·7$. The directive force being greatest at A, it would be the more suitable, as the deviations would be smaller.

(10) Melbourne, H.F. 1·3, deviation+12°; Singapore H.F. 2·1, deviation+7·4°.

(11) Gibraltar, dip 55°, induced $B+3°$; Devonport dip 67°, induced $B-4·5°$.

(12) Sub-permanent $B=+3·7°$. Induced $B=-3·7°$.

(13) Dev. on S. 56° E. due to B and $C=+5·67°$, and to horizontal iron=+1·43°; co-eff. $D=-1·5°$; dev. on S. 22° E.=−10·76°.

(14) Melbourne, dev. from hard iron = −10·05°, from hor. iron=−1·30°.

Singapore, dev. from hard iron=− 6·2°, from hor. iron =−1·3°; deviation on N. 30° W.=−7·5°.

(15) $c=-·013$. At Melbourne, induced $B=-2°$, sub-perm. $B=-6°$. At Singapore, induced $B=+·2°$, sub-perm. $B=-4·2°$.

(16) Port Said, sub-permanent $B=-15°$, induced $B=+2°$, $C=+10°$. New York, sub-permanent $B=-21·7°$, induced $B=+6·43$, $C=+14·5$; head N. 33° 41′ E.

CHAPTER X.

134. The Molecular Theory of Magnetism.—If a magnet is broken into two pieces two complete magnets are formed; if it is broken up into many pieces then every piece is a complete magnet having its red and blue poles, and the assumption is that if this process of disintegration be continued until the magnet is broken up into infinitely small pieces of molecular mass, which is the smallest possible particle in physics, each molecule would be a minute magnet. When the molecules are lying higgledy piggledy the red and blue poles are supposed to point in every conceivable direction, the magnetism of the bar is then hidden or latent; but when an external magnetic force is applied, slightly at first, the north seeking ends of the molecules turn through a small angle and the bar becomes weakly magnetised. As the magnetisation of the bar proceeds the molecules gradually straighten themselves out more and more and the bar becomes more strongly magnetised during the process until, eventually, the molecules are all in alignment and tail on to each other end to end, thus forming a series of magnetic chains passing lengthwise through the bar. The magnet is then said to be saturated. (44 to 48)

135. Theory of Terrestrial Magnetism.—The earth behaves as if it were a magnet having its blue polarity in the north hemisphere and red polarity in the south hemisphere with a fairly well defined neutral zone, or equatorial region between them, the magnetic poles being some distance removed from the earth's poles of rotation. (24 and 25)

This simple hypothesis, however, does not explain fully the distribution, or the intensity of the magnetic state of the earth which must be only skin deep, as magnetism is destroyed by heat, the critical temperature at which this occurs, 700 to 800 degrees centigrade, being reached a few miles below the earth's surface. The earth has been likened to an electro-magnet. It revolves on its axis from W. to E. causing the sun to have an apparent motion from E. to W. and, assuming that electrical energy is emanated from the sun, we can conceive the earth cutting these lines of force and

generating an induced current flowing from E. to W. Assuming this circulation, then on looking downwards on the north pole it would appear as a right-handed current, blue polarity, and on looking downwards on the south pole the current would be left-handed, red polarity. (12)

The origin of the earth's magnetism is, however, not yet a settled question; probably several causes contribute, such as magnetic masses in the earth, electric currents in the earth and in the atmosphere. The appearance of an aurora is usually accompanied by a magnetic storm causing the compass needles over whole regions of the globe to be disturbed with irregular deviations. The intensity of these perturbations is considerably greater in regions nearer to the poles than in lower latitudes, so that only in high latitudes and during aurorae need the navigator be concerned regarding the effect of this discharge of atmospheric electricity on the course he has to steer by his compass.

136. The Magnetic Elements.—The science of terrestrial magnetism is really a science of observation and experimental research in order to provide the means of determining at any place and time the direction and amount of the earth's magnetic force. Three things must be known in order to specify exactly the magnetic condition at any place; these three factors, known as the terrestrial magnetic elements, are:—

(1) The variation, (2) the dip, (3) the intensity of the total magnetic force.

Obviously the three elements are closely related to each other, the variation and dip being directional in character while the intensity is the force, or drawing power, of the earth's magnetism. The variation is the angle contained between the planes of the magnetic meridian and the geographical meridian. It goes through every angle from 0° to 180° E. and 180° W., reaching this maximum between the magnetic and geographical poles.

The dip or inclination of the needle is the angle it makes with the horizontal plane and varies from 0° at the magnetic equator to 90° at the magnetic poles.

137. Magnetic Maps.—Occasional reference has previously been made to the elements, particularly to variation, Art. 26, which is essential to the navigator in setting a compass course and, fortunately for him, it is the most accurately and widely known of the three.

In order to express the results of observations of the magnetic elements made at various places in graphic form, it is usual to draw lines joining these points on a map where the values are equal, and so we have lines of equal variation (isogonic lines) and lines of equal dip (isoclinic lines) as given on Charts I and II.

The value of the total force of the earth rarely enters into magnetic experiments and is consequently resolved into its two components, horizontal force and vertical force. Lines of equal horizontal force and equal vertical force (isodynamic lines) are mapped on Charts IV. and V., hence the reason why four maps are required to give values of the three elements, variation, dip and total force.

138. Magnetic Latitude.—An inspection of the dip chart shows the magnetic equator as the line of zero dip (aclinic line), and the angle of dip gradually increasing to 90° at the magnetic poles. It will be noticed also that the sinuosities of the lines of equal magnetic dip do not differ greatly from each other and resemble somewhat the parallels of latitude, so that, by analogy, they indicate magnetic latitude.

The magnetic field at the surface of the earth is, in general detail and neglecting local irregularities, similar to that due to a very small magnet at the centre of the earth, with its axis making an angle of about 17° with the earth's axis, and from this supposition may be derived the formula

$$\tan \text{dip} = 2 \tan \text{magnetic latitude},$$

which gives approximately the dip at the place, the magnetic latitude being, of course, measured from the magnetic equator.

Example.—The magnetic latitude of Glasgow is 52° N. as estimated from Chart II., find the dip.

$$\begin{aligned} \tan \text{dip} &= 2 \tan 52^\circ \\ ,, &= 2 \times 1{\cdot}28 \\ ,, &= 2{\cdot}56 \\ \therefore \text{dip} &= 69^\circ, \end{aligned}$$

which agrees closely with the actual dip of 70°.

139. Total Intensity.—Still assuming the theory of a magnet at the centre of the earth, the force it would exert at the earth's surface in the region of the magnetic poles should be double the force experienced at the equator, because the magnet would be set "end on" to places at the poles and set "side on" to places near the magnetic equator, with the result that the distribution of magnetic

force at different points of the earth's surface is irregular, and varies in different latitudes according to the law of Biot, which says that the force is approximately proportional to the square root of

$$1+3 \text{ sine}^2 \text{ magnetic latitude.}$$

Example.—Find the total magnetic force of the earth at Glasgow in magnetic latitude 52° N.

$$\begin{aligned} \text{Total force} &= \sqrt{1+3 \cdot \text{sine}^2 52^\circ} \\ \text{,,} \quad &= \sqrt{1+1 \cdot 862} \\ \text{,,} \quad &= \sqrt{2 \cdot 862} \\ \text{,,} \quad &= 1 \cdot 692 \end{aligned}$$

140. Magnetic Foci.—Maps showing lines of equal total force indicate that it reaches its minimum value in equatorial regions and its maximum values in two regions in the North Hemisphere, and in two regions in the South Hemisphere, these areas of maximum intensity being called *magnetic foci.* One of these is in Canada near the Great Lakes of North America, the other in the north-east of Siberia, the former having the higher value of the total force. In the South Hemisphere the two foci are near together to the South of Australia, the stronger one in about 70° S. and 145° E., the weaker one in about 50° S. and 130° E. The force at the foci is between two and three times greater than at the equator.

A mass of magnetic rock near the surface may, however, affect locally the normal values of the magnetic elements. The top of a magnetic rock rising above the surface in the North Hemisphere will, in all probability, have blue polarity at its summit, and the effect of this south pole in attracting the north pole of a compass needle will cause the west variation in Great Britain to be less on its west side, and greater on its east side, than its normal value; whilst south of it the horizontal force will be greater, and north of it less, than the normal value.

141. Earth's Total Force.—The direct determination of the earth's total force is surrounded by difficulties of the nature just referred to, and no satisfactory method has yet been devised to find in one operation the whole magnetic force of the earth at any particular point on its surface.

The method adopted by Gauss, and still practised, was to find by experiment the horizontal force and the dip, both of which can be measured with considerable accuracy, and then to calculate the total force and vertical force from them for that particular place.

The dip is found by means of a dip circle (fig. 87), and the horizontal component by means of a magnetometer (fig. 88), an instrument for measuring magnetic intensity.

142. The Unifilar Magnetometer is a needle suspended by a single thread, and was invented by Gauss in 1836 to determine the absolute

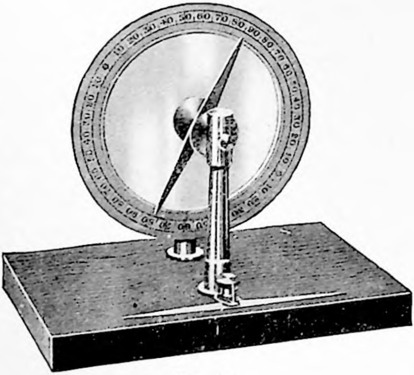


FIG. 87.

value of the earth's horizontal force. It consists of two parts, one part for observing deflections of a needle, the other for observing its vibrations. The deflectional experiment is needed in order to find

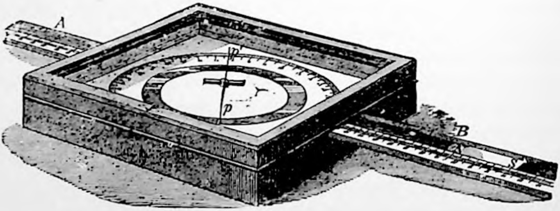


FIG. 88.

the magnetic moment of the needle, that is to say, its turning power; and also to find its moment of inertia, a mechanical factor which depends upon the size, shape and weight of the needle employed and has nothing to do with magnetism. Both these characteristic properties of the needle influence the time of its vibrations. Part

of the experiment is to compare the number of vibrations made in a given time at stations widely separated (Art. 159), and the effect of the magnetic properties of the needle used in the magnetometer have to be eliminated from the results. After various instrumental refinements have been attended to and the requisite calculations made, the values of the magnetic elements at one place relatively to another are determined, or their values may be expressed in absolute units.

143. Relative Force.—The magnetic force of the earth may be expressed in relative values or in absolute values. Relative measure gives the ratio which the force at one place bears to its value at another place, and merely informs us that the value of the elements at a place is a little more or a little less than at another. The standard of reference was originally the value found at a station in South America a century ago where the dip was zero and which, at that time, was supposed to be an indication of the minimum magnetic force at the earth's surface. This assumption, however, has long been known to be erroneous as the direction and the intensity of the earth's force are both subject to irregular and periodic variations, the changes at different places being scarcely comparable one with another, so that a standard basis of reference is required in order to compare the magnetic conditions existing at one epoch with another.

All determinations of magnetic force on board ship and in a laboratory are of the relative class. But these relative values can subsequently be compared with the relative values at a base station at which the absolute force is also known and so, by deduction, the absolute value at the place of observation may also be determined.

144. Absolute Force is the intensity of the earth's magnetic force, or of a magnet, expressed in the fundamental quantities of the centimetre gramme second (C.G.S.) system of units, in which

A CENTIMETRE is the unit of length.
A GRAMME is the unit of mass.
A SECOND is the unit of time.

The unit of force exerted by a magnet, or by the earth, is called ONE DYNE. It is defined as that force, which, acting for one second on a mass of one gramme, gives to it a velocity of one centimetre per second. These units are called "absolute units," the term absolute, introduced by Gauss, meaning that they are in-

dependent of the size of any particular instrument, or of the value of gravity at any particular place, or of any arbitrary quantity other than the three standards of length, mass and time.

The following articles in this chapter deal with the elementary theory associated with some of the usual laboratory experiments leading up to the method adopted by Gauss to determine the absolute horizontal component of the earth's magnetic force.

145. C.G.S. Units.—The CENTIMETRE is equal to ·3937 inches. The GRAMME represents the mass of a cubic centimetre of water at 4° C., and is equal to 15·432 grains.

From these fundamental units other units are derived and applied universally in physical science; for example, THE UNIT OF VELOCITY is a "velocity of one centimetre per second."

THE UNIT OF ACCELERATION is that acceleration which imparts unit velocity to a body in a unit of time, or the velocity of "one centimetre per second."

THE UNIT OF FORCE is that force which acting for one second on a mass of one gramme gives to it a "velocity of one centimetre per second." This unit is called a DYNE and is used throughout magnetic measurements.

These units at first glance are somewhat elusive and not readily accepted. Perhaps the simplest unit of force is a given weight, say that of one gramme. But weight is the downward attraction due to gravity, and as the earth's gravitational force is greater at the poles than elsewhere, the weight of a mass of one gramme in consequence thereof varies with the latitude and weighs greatest at the poles and least at the equator. The value of gravitational force not being constant at the earth's surface is unsuitable as a unit and the DYNE is used instead because it is a unit of constant value in all latitudes.

When any weight, one gramme for example, falls from rest it is pulled down by the earth and its velocity increases every moment. The rate of its increase of velocity is called acceleration.

146. Acceleration.—When a unit force has been acting on a mass of one gramme the velocity would be one centimetre at the end of the first second, two centimetres at the end of the next second, three centimetres at the end of the third second and so on. When the force of gravity, which is not unit force, has been acting for one second the gramme has a certain velocity called g, which at Greenwich = 981·1 centimetres per second (approximately 32·2

feet per second). At the equator $g=978\cdot1$; at the North Pole $g=983\cdot1$, hence the weight of a gramme at Greenwich $=981\cdot1$ dynes; at the equator it weighs $978\cdot1$ dynes; at the North Pole it weighs $983\cdot1$ dynes.

147. **The Magnetic Field** of a magnet is the area covered by the lines of force and throughout which its influence extends. The intensity of this magnetic flux, or atmosphere, is greatest near its poles and diminishes rapidly as the distance from the magnet is increased. The lines of force are conceived to be crowded together near the poles and spreading out more and more as the distance becomes greater, so that the quantity of magnetism flowing into space may be represented by the number of lines of force passing through a given area. The intensity at any part of the field is represented by the number of magnetic lines passing through a square centimetre at right angles to the direction of the field.

The intensity of a magnetic field, whether it be that of the earth or a magnet, is measured by the force the field exerts upon a unit magnetic pole, whether it moves it or not. A magnetic field has unit intensity if it pushes a unit pole with a force of one dyne.

"A UNIT MAGNETIC POLE" is one of such strength that, when placed at a distance of one centimetre from a similar pole of equal strength it repels it, or attracts it, with a force of one dyne.

148. **The Unit of Intensity** is called a GAUSS, and is the number of magnetic lines to the square centimetre emitted by a unit pole at a distance of one centimetre.

When the fields of two magnets overlap, the lines of force are not destroyed but react on each other and take up a new direction and acquire a new intensity which is the resultant of the two forces at the point of contact. The reciprocal action of one pole on another creates a new field which depends on the distance separating the poles as well as the quantity of magnetism. This creates a difficulty when attempting to determine the absolute force of a magnet, or of the earth, by means of its effect on another magnet, because the combined effect of the two contiguous magnets is to create a new field, and any experiment conducted within this field is vitiated by their joint action. The difficulty is to get rid of the disturbance caused by the two poles of the magnet we wish to ignore, but this will be referred to further on.

149. **Laws of Magnetic Force.**—*First Law.*—Like magnetic poles repel each other; unlike poles attract one another.

Second Law.—The force exerted between two isolated poles varies directly as the product of their strengths, and inversely proportional to the square of the distance between them.

The first law is well understood but the second one, the law of inverse squares, may require some further explanation. A magnetic pole is said to be of unit strength when it exerts upon a similar pole a force of one dyne at a distance of one centimetre between them. The strength of a pole can be estimated by observing the magnetic force it exerts upon another magnet.

$$F = \frac{m_1 \times m_2}{d^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; \text{I.}$$

where F is the force in dynes, m_1 and m_2 the respective strength of the poles, and d the distance between the poles.

Example.—What force does a magnet pole, the strength of which is 9 units (m_1) exert upon a pole whose strength is 16 units (m_2) placed 6 centimetres (d) away from it?

$$F = \frac{m_1 \times m_2}{d^2} = \frac{9 \times 16}{6 \times 6} = 4 \text{ dynes.}$$

Example.—A pole of strength 40 units (m_1) acts with a force of 32 dynes (F) upon another pole 5 centimetres (d) away. What is the strength of that pole?

$$F = \frac{m_1 \times m_2}{d^2}, \therefore 32 = \frac{40 \; m_2}{5 \times 5}, \therefore m_2 = 20 \text{ units.}$$

The same law applies in general terms to the magnetism of a ship in causing deviation on the compass, the deviation in this case being the result of the force exerted by the ship magnet on the compass, so that the force varies directly as the product of the pole strengths of the compass needle and ship magnet, and inversely proportional to the square of the distance between them. The ship, however, is a very irregular and unstable magnet and not amenable to exact measurement.

150. Magnetic Moment.—Moment means turning power and the tendency of a magnet to turn, or to be turned by another magnet is called its magnetic moment, the moment being equal to the product of the strength of one of its poles and the distance between its poles.

$$M = m \, 2 \, l \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; \text{II.}$$

where M = the moment of the magnet.
m = the strength of one pole.
$2\,l$ = the length between its poles.

When a horizontally suspended magnet is turned through a small angle and released it then oscillates to and fro with a regular pendular motion, its amplitude of deflection gradually becoming smaller until finally it comes to rest. The time occupied in making one vibration is called the period of the magnet, and the period may be increased or decreased by altering the shape, size, weight or magnetic moment of the magnet. Such alterations, however, affect the moment of inertia of the magnet, inertia being the tendency of a body at rest to remain at rest, or when moving to keep on moving in the same direction as it was going.

151. The Moment of Inertia of a magnet depends upon its mass and upon the way in which it is distributed. This may readily be demonstrated by noting the time taken by a horizontally suspended needle to make a certain number of vibrations. If small weights are now hung on each half of the needle thus increasing its mass, it will be found, on again vibrating it, that the needle makes fewer vibrations in the same time, "the period of the needle is lengthened when its mass is increased."

Suppose the weights are now removed and the needle is strengthened by further magnetisation, thus increasing its magnetic moment, it will be found, on again vibrating it, that the needle makes a greater number of vibrations in the same time, hence " the period of the needle is shortened when its magnetic moment is increased."

It is understood, of course, that a magnetised needle points north when under the influence of the earth's normal magnetic field, but suppose we now strengthen the magnetic field in the vicinity of the needle by placing the blue pole of a magnet a short distance away from its north end, it will be found, on again vibrating the needle, that it makes a greater number of vibrations in the same time, hence, "the period of the needle is shortened when the magnetic field is strengthened."

For the purpose of making certain magnetic measurements it is necessary to know the moment of inertia (K) of the magnets.

For rectangular magnets $K = W \dfrac{a^2+b^2}{12}$ . . . . III.

For cylindrical magnets $K = W\left(\dfrac{l^2}{12}+\dfrac{r^2}{4}\right)$ . . IV.

P

where K = the moment of inertia.
W = the mass or weight of the magnet.
a = the length and b the breadth of the surface bounding a and b.
l = the length of the axis of the cylinder.
r = the radius of the end of the cylinder.

Example.—A rectangular magnet is 10 centimetres long, 2 centimetres broad and weighs 111 grains, find its moment of inertia.

$$K = W\frac{a^2+b^2}{12} = 111\frac{10^2+2^2}{12} = 962 \text{ C.G.S. units.}$$

Example.—A cylindrical magnet 10 centimetres long and radius ·5 centimetres weighs 100 grains. Find its moment of inertia.

$$K = W\left(\frac{l^2}{12}+\frac{r^2}{4}\right) = 100\left(\frac{10^2}{12}+\frac{\cdot5^2}{4}\right) = 839{\cdot}6 \text{ C.G.S units.}$$

152. Deflection Magnetometer.—A magnetometer is an instrument for measuring magnetic force, the simplest form for approximate work being as arranged in fig. 88. The pivoted needle is made very short and its angle of deflection on the graduated circle is read by means of a light aluminium pointer ($p\ p^1$) attached to the needle at right angles to its magnetic axis. The box containing the compass needle is placed on a cross arm ($A\ B$) divided into centimetres so that the exact distance may be measured between the needle and the magnet ($N\ S$) employed. The magnetometer is used for finding experimentally the moment of a magnet and the strength of its poles, also the reciprocal action between magnets.

The experiments would be of the simplest character if magnets had one pole only, but the resultant effect of both poles acting simultaneously on the compass needle has to be taken into account. It is possible to demonstrate the effect of a single pole on the compass needle by using a very long magnet and holding it at an angle to the vertical, so that its lower pole is in the same horizontal plane as the needle, and its upper pole exactly over the centre of the needle as in fig. 89, thus acting as a "one pole" magnet.

By experiment it may be shown that when the distance ($N\ C$) of the lower pole is changed the angle of deflection is found to vary inversely as the square of the distances between the pole and the needle.

If θ and θ_1 represent the angles of deflection of a compass needle corresponding to distances $C\,N$ and $C\,N_1$, then

$$\frac{\theta}{\theta_1}=\frac{(C\,N_1)^2}{(C\,N\,)^2}$$

Example.—A "one pole" magnet when held in position $N\,S$ as in fig. 89 produces 12° deflection (θ) with its lower pole in the same horizontal plane as the compass and 10 centimetres ($C\,N$) from it, what will the angle of deflection (θ_1) be when it is in the $N_1\,S_1$ position the lower pole being now 20 centimetres ($C\,N_1$) from the compass?

$$\frac{\theta_1}{\theta}=\frac{(C\,N)^2}{(C\,N_1)^2}\qquad\frac{\theta_1}{12}=\frac{10^2}{20^2}\quad\therefore\quad\theta_1=3°$$

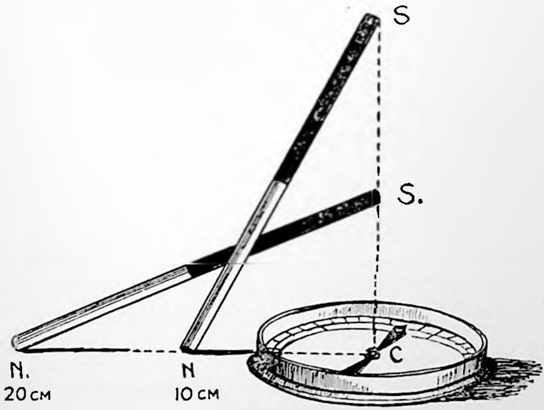


FIG. 89.

153. Moment of Magnetic Force.—When two equal and opposite forces act on a balanced magnetic needle they form a "couple," and simply tend to turn it round.

In fig. 90 $N\,S$ is a needle, H being the direction of the earth's horizontal field, one force acting on the north pole and the other on the south pole, but both tending to turn the needle into the magnetic meridian, the double action forming a couple the measure of which is obtained by multiplying one of the forces by the perpendicular distance between them. The force (F) acting on each pole = the pole strength (m) of the needle multiplied by the horizontal component (H) of the earth's magnetism at the place.

On N, the force $F = +m\,H$, on S., the force $F = -m\,H$ . .V.
Where F = the force on each pole,
m = the strength of each pole,
H = the horizontal component of the earth's intensity.

Now, the MOMENT of the couple (G) tends to draw the needle into the meridian and is the force acting on the pole N multiplied by the distance $A\,S$,

thus $G = m\,H \times A\,S = m\,H \times 2\,l$ sin. θ.

Where $2\,l$ = the length of the needle.
θ = the angle of deflection.

But by Eq. II., $M = 2m\,l$

$\therefore\ G = M\,H$ sin. θ . . . . . VI.

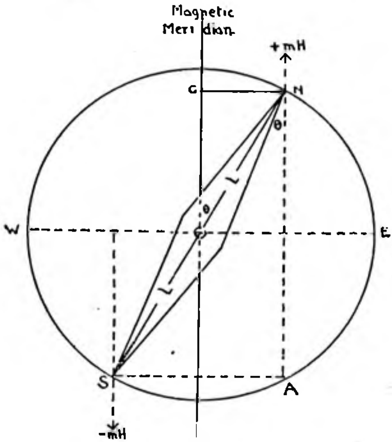


FIG. 90.

Hence the moment of the couple tending to bring the needle into the meridian is equal to its magnetic moment (M) multiplied by the earth's horizontal force (H) multiplied by the sine of the angle of deflection (θ).

It will be noticed that the distance $A\,S$ increases as the needle is turned more obliquely to the meridian so that the length $A\,S$ (or its half length $C\,N$) increases from zero to maximum as the angle of deflection increases from 0° to 90°, thus the moment of the couple

increases as the sine of the angle of deflection, because sine $0° = 0$, and sine $90° = 1$.

154. A Geometrical Illustration.—The effect of a disturbing magnet on a compass needle varies as the sine of its azimuth. This may be illustrated geometrically as in fig. 91, in which the compass is supposed to be at *C*. The disturbing magnet when in position *S N* causes no deflection of the needle; the moment of the couple is zero; the azimuth of the magnet is 0°.

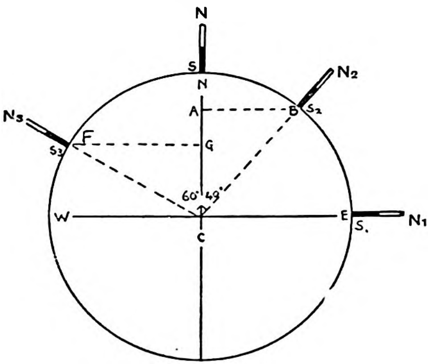


FIG. 91.

The maximum moment operates when the magnet is at right angles to the needle as at $S_1 N_1$, its azimuth being then 90°, so that the biggest deflection appears when the disturbing magnet is due east or west of the compass. If the degrees of this maximum deflection be represented, from any convenient scale, by the length of the horizontal line *C E*, then, as the magnet is moved in azimuth round the compass, the angle of deflection will get smaller as it approaches north and the length of *A B* will represent the degrees of deflection due to the magnet in the $S_2 N_2$ position.

But $A\ B = C\ B$ sine $N\ C\ B$ = maximum deflection × sine azimuth. Similarly, the deflection caused by the magnet when placed in the $N_3 S_3$ position is represented by $F\ G$, and $F\ G = C\ F$ sine $N\ C\ F$.

Example.—The azimuth of a magnet is N. 40° E. and causes 10° deflection when placed end on to a compass, what deflection will it cause when its azimuth is N. 60° W?

From fig. 91

$$\frac{F\,G}{A\,B} = \frac{\text{sine } 60^\circ}{\text{sine } 40^\circ} \therefore F\,G = \frac{10 \text{ sine } 60}{\text{sine } 40} = 13{\cdot}5^\circ$$

155.—Law of Tangents.—Referring to fig. 92 it will be observed that if a needle be deflected by an external magnetic force placed at right angles to it, that is due east of the needle, and it comes to rest, the needle has two couples acting upon it, one, the earth's

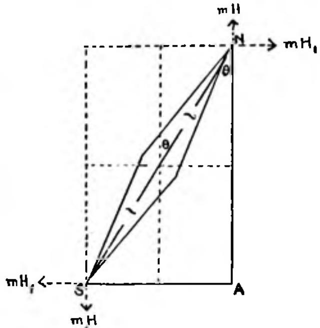


FIG: 92.

horizontal force ($m\,H$) tending to turn it into the meridian, and the other, a force ($m\,H_1$) tending to turn it perpendicular to the meridian. The needle being at rest in equilibrium the moment of one couple = the moment of the other couple, so that the force ($m\,H_1$) in the east-west direction $\times A\,N$ is equal to the force ($m\,H$) in the north-south direction $\times A\,S$, and this may be written,

$$\text{couple due to } H_1 = \text{couple due to } H$$

$$m\,H_1 \times A\,N = m\,H \times A\,S$$

$$m\,H_1 \times 2\,l \cos \theta = m\,H \times 2\,l \sin.\,\theta$$

$$H_1 = \frac{m\,H\,2\,l \sin.\,\theta}{m\,2\,l \cos.\,\theta} \quad \text{but } m\,2\,l \text{ cancels}$$

$$\therefore H_1 = H \tan.\,\theta \quad . \quad . \quad . \quad . \quad \text{VII.}$$

156. The Oscillation Magnetometer enables us to find the comparative moments of two magnets by observing the number of vibrations they make in equal times, or the times taken by them to make an equal number of vibrations. The moments vary directly as the square of the vibrations when the time is constant, and

inversely as the square of the times when the number of vibrations is constant.

$$\frac{M_1}{M_2} = \frac{(n_1)^2}{(n_2)^2} = \frac{(t_2)^2}{(t_1)^2}$$

where M_1 and M_2 are the moments of the magnets.
n_1 and n_2 the number of vibrations in equal times.
t_1 and t_2 the time in seconds to make an equal number of vibrations.

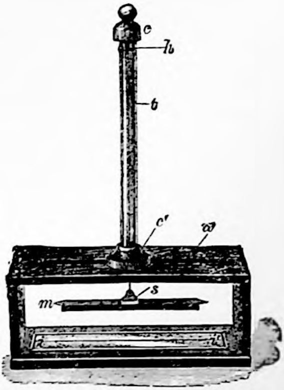


FIG. 93.—Oscillation Magnetometer.

The magnet is placed in a small stirrup which is suspended by a silk fibre and protected by a glass cover. Distances from the centre of the suspended needle, and the arcs through which the needle vibrates, are read from suitably placed scales of measurement.

The instrument as illustrated consists of a box with sliding glass doors back and front, and a narrow slit (*w*) at the top to which is fixed a glass tube (*t*) with a brass cap (*c*) and a hook (*h*). One end of a silk fibre is attached to the hook which is capable of being raised and lowered, and at the other end a stirrup (*s*) for carrying the magnet (*m*) is fixed. A strip of mirror glass with an index line (*ii*) scratched across its middle is fixed on the base of the box. The observer looks through the glass slit and times the transit of the magnet (*m*) across the index line (*ii*).

When a magnet is placed on the stirrup it can be drawn out of the meridian by bringing another magnet carefully up to it. It will then oscillate about its position of rest until, finally, it again becomes stationary. Whether the magnet be drawn through a small angle or a large angle it always makes the same number of oscillations in the same time.

157. The Oscillating Magnet is governed by laws similar to the laws which govern the swinging of a pendulum, and just as the time of oscillation of a particular pendulum varies with the force of gravity and can be calculated for any given latitude, so the time of one oscillation of a particular magnet when suspended horizontally varies with the earth's horizontal force and can be calculated for any particular place, but, in each case, the moment of inertia of the oscillating body must be known. The moment of inertia of a magnet depends upon its shape and weight as described in Art. 151 and the time of one oscillation is determined by the formula

$$t^2 = \frac{\pi^2 K}{M H} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{VIII.}$$

where t is the time in seconds of one oscillation.
K the moment of inertia of the magnet.
M the magnetic moment of the magnet.
H the horizontal component of the earth's force.
π in radian measure $= 3{\cdot}1416$.

An oscillation in this case means the movement from one extreme position to the other, as distinguished from a vibration which is defined usually as a complete to and fro movement of the magnet.

Equation VIII may also be written $M H \quad = \quad \dfrac{\pi^2 K}{t^2}$

158. To Compare the Moment of Two Magnets of the same shape and weight, suspend one magnet in the oscillation stirrup and find how many vibrations it makes in one minute. Repeat this operation with the second magnet. Suppose in one minute magnet A made 30 vibrations (n_1) and magnet B made 40 vibrations (n_2), then

$$\frac{\text{moment of } A}{\text{moment of } B} = \frac{M_1}{M_2} = \frac{(n_1)^2}{(n_2)^2} = \frac{30^2}{40^2} = \frac{9}{16}$$

or $M_1 : M_2 :: 9 : 16$

Suppose, however, that magnet A made 30 vibrations in 80 (t_1) seconds and magnet B made the same number of vibrations in 60 (t_2) seconds,

then $$\frac{\text{moment of } A}{\text{moment of } B} = \frac{M_1}{M_2} = \frac{(t_2)^2}{(t_1)^2} = \frac{60^2}{80^2} = \frac{9}{16}$$

or $M_1 : M_2 :: 9 : 16$.

159. Relative Value of the Earth's Horizontal Force.—By using the same deflecting magnet at various widely separated places a good comparative value of the earth's H.F. may be found if care be taken to keep the magnet at the same temperature, and not to use it roughly during transit. Place the magnet in the oscillating stirrup and deflect it. Suppose it requires 60 seconds to make 30 vibrations at a place A, but requires 70 seconds when vibrated at a place B a few hundred miles distant, then

$$\frac{\text{H.F. at place A}}{\text{H.F. at place } B} = \frac{H_1}{H_2} = \frac{(t_2)^2}{(t_1)^2} = \frac{70^2}{60^2} = \frac{1{\cdot}36}{1}$$

or $H_1 : H_2 :: 1{\cdot}36 : 1$, which indicates that the H.F. at A is 1·36 times greater than at B.

160. The First Position, or tangent "A" position of Gauss is when the deflecting magnet is placed end on to the needle as in fig. 94.

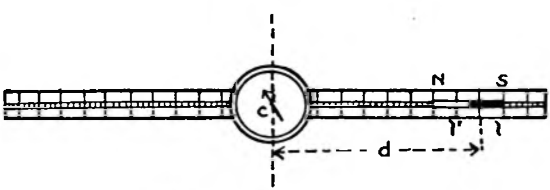


FIG. 94.

In this position the force exerted by the magnet is found to vary directly as the magnet moment (M) and inversely proportional to the cube of the distance (d) as measured between the centre of the magnet and the compass needle, the equation $F = \frac{2M}{d^3}$ being deduced as follows:—

F = the force required.
M = the moment of the magnet.
m = the strength of each pole.
$2l$ = the length of the magnet.
C = the position of a unit pole at the centre of the compass.
d = the distance of C from the centre of the magnet.

Then the distances of the nearer pole and the further pole from C are respectively equal to $(d-l)$ and $(d+l)$

From equation I, the force of one pole $F = \frac{m}{d^2}$

so that the force due to N $= \frac{m}{(d-l)^2}$

and the force due to S $= \frac{m}{(d+l)^2}$

and the resultant of the two forces acting on the unit pole C will be

$$F = \frac{m}{(d-l)^2} - \frac{m}{(d+l)^2}$$

$$F = \frac{m\,(d+l)^2 - m(d-l)^2}{(d^2-l^2)^2} = \frac{4\,m\,l\,d}{(d^2-l^2)^2}$$

$$F = \frac{m \times 2\,l \times 2\,d}{(d^2-l^2)^2}$$

But by Equation II. the moment (M) of a magnet $= 2\,m\,l$

$$\therefore F = \frac{M \times 2\,d}{(d^2-l^2)^2}$$

and by Equation VII. $F = H \tan. \theta = \frac{M \times 2\,d}{(d^2-l^2)^2}$

$$\therefore M = \frac{H\,(d^2-l^2)^2}{2\,d} \tan. \theta$$

This is known as the exact formula for finding the moment of a magnet; but the length ($2l$) of the magnet in these experiments should always be small in comparison with the distance (d), so that l^2 may be dropped out of the equation without making any appreciable difference, and as a first approximation we may

$$\text{for } M = \frac{H\,(d^2-l^2)^2}{2\,d} \tan \theta$$

$$\text{write } M = \frac{Hd^4}{2d} \tan.\ \theta = \tfrac{1}{2}\, d^3\, H \times \tan\ \theta \quad \ldots \text{IX.}$$

and this is known as the approximate formula.

This may also be written as $\frac{M}{H} = \frac{1}{2}\, d^3 \tan.\ \theta$

Example.—A magnet 10 cms. long, placed in the end on position, deflects the needle 45° when their centres are 50 cms. apart at a place where the earth's horizontal force is 0·18. Find the magnetic moment of the magnet and the strength of its poles.

$M = \frac{1}{2}\, d^3\, H \tan.\ \theta$

$M = \frac{1}{2} \times 50^3 \times 0{\cdot}18 \times \tan 45°$ from which the

Magnetic moment $M = 11250$ C.G.S. units.

Now apply Equation II. to find the pole strength (m).

$M = 2\, m\, l$

$$\therefore m = \frac{M}{2l} = \frac{11250}{10} = 1125 \text{ C.G.S. units.}$$

Using the exact formula the result would be as follows:—

$$M = \frac{H\ (d^2 - l^2)^2}{2d} \tan\ \theta.$$

$$M = \frac{\cdot 18\ (50^2 - 5^2)^2}{2 \times 50} \tan 45°$$

from which the moment $M = 11026$ C.G.S. units and the pole strength $= 1102{\cdot}6$ C.G.S. units by Equation II.

161. **The Second Position** or tangent "*B*" position of Gauss is with the magnet placed broadside on to the needle as shown in fig. 95. In this case the magnet deflects the needle with half the force it exerts when in the end on position, and

the moment $M = d^3\, H \tan.\ \theta \ldots$ X

Example.—A magnet 15 cms. long is placed broadside on and deflects the needle 15°, the distance of its centre being 35 cms. from the compass at a place where the earth's horizontal force is 0·18. Find the moment of the magnet and its pole strength.

$M = d^3\ H \tan.\ \theta = 35^3 \times 0{\cdot}18 \times \tan.\ 15°$

from which the moment $= 2068$ C.G.S. units.

From Equation II., $M = 2\, m\, l$.

$$\therefore \text{Pole strength } m = \frac{M}{2l} = \frac{2068}{15} = 137 \cdot 9 \text{ C.G.S. units}$$

FIG. 95.

162. Comparison of Moments by Deflection.—The magnetometer may also be used for comparing the magnetic moments of two magnets by placing one magnet on the cross arm at a known distance from the compass, then placing the other magnet on the opposite side and adjusting its distance from the compass so that the joint effect of the two magnets will balance the needle. A comparison of their magnetic moments may then be expressed in terms of their respective distances. If the magnets are named A and B and their respective distances from the centre of the compass d_1 and d_2 then

$$\frac{\text{moment of } A}{\text{moment of } B} = \frac{(d_1)^3}{(d_2)^3}$$

A comparison may also be made by placing magnet A on the magnetometer when set up for the "A" position of Gauss, that is with the graduated arms at right angles to the meridian and the magnet end on to the compass, and noting the deflection of the needle, say 20° (θ_1). Then replace magnet A with magnet B in exactly the same position and note the deflection it produces, say 8° (θ_2), and then apply Equation IX to find the moment as follows:—

$$\frac{\text{moment of } A}{\text{moment of } B} = \frac{M_1}{M_2} = \frac{\frac{1}{2} d^3 H \tan.\ \theta_1}{\frac{1}{2} d^3 H \tan.\ \theta_2}$$ but $\frac{1}{2}\ d^3 H$ cancels out as they are the same for both magnets A and B, so that

$$\frac{M_1}{M_2} = \frac{\tan \theta_1}{\tan \theta_2} = \frac{\tan 20°}{\tan 8°} = \frac{\cdot 364}{\cdot 140} = \frac{2 \cdot 6}{1}$$

therefore $M_1 : M_2 :: 2 \cdot 6 : 1$

163. Horizontal Force in Absolute Measure.—It is impossible to keep the magnetic moment of a magnet the same during its passage from place to place as the moment varies with change of temperature, loss of magnetism and rough handling, hence the accuracy of relative values cannot be relied upon. But the magnetic intensity of the earth at a place can be found without comparing it with that at another, and the immediately preceding articles have been

leading up to Gauss' method of determining the absolute horizontal component of the earth's total magnetic force and which we shall now try to describe in detail.

It was shown by Eq. VIII. that $M H = \frac{\pi^2 K}{t^2}$

and by Eq. IX that $M/H = \frac{1}{2} d^3 \tan \theta$,

M being the moment of the magnet employed.

H the horizontal force of the earth, now required.

θ the angular deflection of the needle in the magnetometer.

d the distance of the magnet from the needle.

K the moment of inertia of the magnet.

t the time of making a given number of vibrations.

$\pi = 3{\cdot}1416$.

The right hand side of these equations can be found and the quantity reduced to a simple number, so that if $M H = X$, and $M/H = Y$, then by division $M H \div M/H = H^2 = X/Y$. The object in view, therefore, is to find values for the right hand side of these equations and divide one by the other. Perhaps the procedure may best be explained by describing the following experiment.

(*a*) The rectangular magnet used in the experiment was 10 centimetres long, 2 centimetres wide and weighed 111 grammes. Its moment of inertia found by Eq. III. was

$$K = W \times \frac{a^2 + b^2}{12} = 111 \times \frac{10^2 + 2^2}{12} = 962.$$

(*b*) The magnet was then placed in the stirrup of the oscillating magnetometer, fig. 93, when the average time of a series of 60 oscillations was found to be 10m 18s., the time of one oscillation was therefore $618/60 = 10{\cdot}3$ seconds.

By Eq. VIII. $M H = \frac{\pi^2 K}{t^2} = \frac{(3{\cdot}1416)^2 \times 962}{(10{\cdot}3)^2} = 89{\cdot}5$

(*c*) The magnet was then placed on the deflection magnetometer (fig. 94) in the "A" position of Gauss, that is, end on to the needle as described in Art. 160. The mean of a series of deflections made with the magnet placed east of the compass, and again when placed west of it, at a distance of 24 centimetres was 20° 30′ (nat. tan. 20° 30′ = ·374).

By Eq. IX $M/H = \frac{1}{2} d^3 \tan \theta = \frac{1}{2} (24)^3 \times \cdot 374 = 2585$

$$MH \div M/H = H^2 = \frac{89 \cdot 5}{2585} = \cdot 03462$$

$$H = \sqrt{\cdot 03462} = \cdot 186$$

The absolute horizontal force of the earth is therefore ·186 dynes.

The foregoing is a brief explanation of the method usually adopted for simple laboratory experiments to determine the variation and absolute horizontal force of the earth.

Example.—If an iron pillar 2 metres long and 8 centimetres diameter is magnetised by vertical induction from the earth's field, find the intensity of magnetisation if the magnetic moment=1000 C.G.S. units. Find also the magnetic susceptibility if the earth's force=0·5.

Intensity of magnetisation = Moment/volume.

the moment in this example = 1000 c.g.s

the volume of the pillar $= \pi r^2 l = \frac{22}{7} \times 16 \times 200$ c.m.

$= 10057$ cu. cm.

$$\text{Intensity} = \frac{\text{moment}}{\text{volume}} = \frac{1000}{10057} = \cdot 1. \quad \textit{Ans.}$$

$$\text{Susceptibility} = \frac{\text{intensity}}{\text{magnetising force}} = \frac{\cdot 1}{\cdot 5} = \cdot 2. \quad \textit{Ans.}$$

QUESTIONS.

1. Describe the molecular theory of magnetism. (134)

2. State briefly what you know of terrestrial magnetism. (135)

3. What are the three magnetic elements? (136)

4. Why are four charts required to record the magnetic elements? (137)

5. What relation is there between the earth's magnetism and the variation and dip of the needle? (136)

6. Does magnetic dip change in proportion to change of geographical latitude? Give a formula for finding the dip at a place. (138)

7. What is meant by the earth's magnetic intensity? Give a formula by which the approximate intensity at a place may be found. (139)

8. State what you know of magnetic foci. (140)

9. Describe Gauss's method of determining the absolute horizontal force of the earth. (141) (163)

10. What is meant by relative and absolute magnetic force? (144)

11. What is meant by a unit magnetic pole? (147)

12. Describe a magnetic field and how its intensity is measured. (147)

13. Prove geometrically that if the force of a magnet is given its force can be found for any other azimuth. (154)

14. What is the relation between the deviation appearing on the compass and the magnetic forces causing it? (149)

15. When has a magnet the greatest moment on the compass needle and in what proportion does it change? (154)

16. What is the ratio between two magnetic forces? How does it vary? Give a formula for finding the ratio. (149)

17. Describe what is meant by the moment of inertia of a magnet, and how it may be increased or decreased. (150-151)

18. Describe a simple form of magnetometer and what it is used for. (152)

19. How may the magnetic moment of two magnets be compared? (158) (162)

20. How may the value of the earth's horizontal force at two places relatively to each other be found? (159)

CHAPTER XI.

NOTE ON THE GYRO-COMPASS.

The magnetic compass, notwithstanding its frailties and limitations, has been the faithful guide of ancient mariners and modern navigators alike. It isn't nice to think disparagingly of a friend who has added to our comfort and security under many skies, from the languishing calms of the equator to the biting blizzards of Cape Horn and the North Atlantic. But, is it not possible that the mariner's compass has reached the limits of its usefulness?

A line drawn from any position on the earth's surface to the geographical pole is a true meridian. This is the only immutable line of reference available on this planet which appeals to our intellect. The true meridian is the most natural and logical standard to which the direction of any other line drawn on the surface of the globe can be referred. In all navigational calculations the track of the ship is referred directly, or indirectly, to the geographical meridian, and we cannot conceive of any navigator, other than the most obstinate and conservative of seamen, who would not gladly welcome the advent of an instrument of precision which would indicate to him continuously, unswervingly, unerringly, the true north point of the horizon.

Does such an instrument exist? It is claimed for the gyro-compass that it can do all this, and more. Its capabilities have been proved in naval ships, it is indispensable to the navigation of a submarine, and it is now being supplied to a few merchant ships where it is still looked upon, like all revolutionary and novel inventions, with a certain amount of suspicion. Practical experience as to its utility under Mercantile Marine conditions will no doubt create confidence in its possibilities.

The directional properties of the gyro-compass have nothing whatever to do with magnetism. It depends for its action entirely on mechanical and dynamical laws; it is a complex piece of mechanism electrically driven, but simple to read and *points true north.* The

essential element is a fast spinning wheel rotating at anything up to 20,000 revolutions per minute depending on the type of machine. The rest of the installation is more complicated but it is wholly subordinate to the desired object of getting this wheel to spin, when mounted and balanced on board ship in conformity with certain well-known laws in dynamics which, when satisfactorily accomplished, enables the wheel to bring its axle into the plane of the true meridian, and to keep it pointing parallel to the true N. and S. points of the horizon, under all seagoing conditions.

The force with which the gyro-compass seeks the north depends amongst other things, on the speed of the spinning wheel multiplied by the speed at which the earth rotates on her axis. The latter cannot be accelerated, the earth makes only one complete turn per day, so the wheel is rotated as fast as possible consistent with the consequent rise of temperature and the strength of the materials and their connections. The faster the wheel spins the greater is the directive force of the compass and, if the earth rotated faster (fortunately man has no control over this factor) the greater also would be the energy with which the axle of the spinning wheel would point to the north. The power with which the gyro-compass holds on to the true north is many times greater than the effort of a balanced needle in finding the magnetic north.

That a rotating body when passing through the air tries to keep its axis pointing parallel to its original direction is readily accepted. When playing deck quoits the thrower usually gives the ring a spin so that its axle, if it had one, may keep parallel to the pin at which he aims ; a plate, a biscuit or any plane surface must be spun from the hand when thrown into the air if we wish to control the direction of its flight. The art of playing diabolo depends mainly on the rapidity of the spin given to the top when thrown into the air ; an ordinary top remains upright only when it is spinning fast, and only when its rotary speed slows down does its axis incline more and more to the vertical until, owing to friction and gravity, it finally falls on its side. A wheel spun swiftly along a road remains upright, and if sent in an east-west direction its axle points north and south, and the axle will continue to point N. and S. so long as the wheel remains upright. But the faster the wheel spins, neglecting obstacles and friction, the straighter it goes, the more perfect is its balance and the more accurately does its axle point to the north. Conceive this imaginary wheel to be travelling to the east and that

we are running to the eastward after it, then it will be obvious to anyone who has played with a hoop that whenever the wheel is inclined over a little to the right hand its path will also bend to the right hand. At the same time the left hand end of the axle, that is the north pointing end, will be tilted upwards at an angle corresponding to the inclination of the plane of the wheel to the vertical, and as the wheel gradually turns in its path to the right hand so also will the north end of the axle turn to the right of its original direction, that is to the eastward of north, and, eventually, when the wheel is travelling to the south the axle will be pointing in an east-west direction, the north end being to the east. (*See* fig. 10.)

Instead of inclining this east-going wheel to the right hand suppose we caused it to heel over a little to the left hand, then it would at once begin to trace out a path which also bends to the left hand ; but now the left, or north, end of the axle will be depressed and the south end tilted upwards, and as the wheel continues to follow its circular track the north end of the axle will turn, or precess as it is technically called, to the westward of north at a corresponding rate. Note particularly that when the N. end of the axle is depressed it turns (precesses) to the westward, but when elevated it precesses to the eastward. It will also be noted that this east-going wheel when looked at side on from the south has a clockwise rotation about its axle, and when looked at side on from the north the rotation is counter-clockwise, that is, opposite to the hands of a watch. This is the direction of rotation usually adopted in single wheel compasses.

It is a curious fact, but nevertheless one which is amenable to the known laws of dynamics, that rotating bodies such as machinery wheels and all bodies in circular motion are trying to direct their axles to the pole star and are only restrained from doing so by the feebleness of their effort and the nature of their mountings. The earth is a gyrostat and its axis is kept pointing steadily in the same direction owing to the spin imparted to it "in the beginning."

Imagine a small wheel rotating at a high speed and mounted as in fig. 1, in short a gyroscope. The wheel rotates on its axis $E\ F$, the ring on the gimbals $D\ C$, and both rotate together on the vertical spindle A ; it is said to have three degrees of freedom, it can move in three planes simultaneously, (1) about its own axis, (2) about a horizontal axis, (3) about a vertical axis.

Now think of a horizontal turn-table mounted centrally on a vertical axis and free to rotate ; assume it to be at rest for the

moment. Pick up the gyroscope, the wheel of which is spinning swiftly, and note the direction of its axle, place it on the turn-table, nothing happens, the axle points in the same direction. Begin turning the table, the gyroscope is carried round with it but still nothing happens, the axle of the gyro wheel (keep your eye on the axle E F) points in the same initial direction. If the axle is horizontal to begin with it remains horizontal ; if tilted upwards at any angle it will remain at that particular angle and continue to point

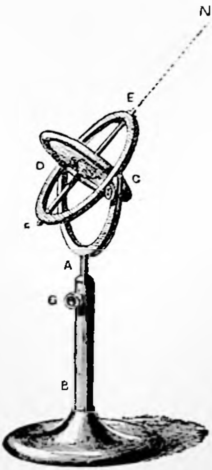


FIG. 1.—Gyroscope with three degrees of freedom. The axle of the wheel keeps parallel to the direction initially given to it.

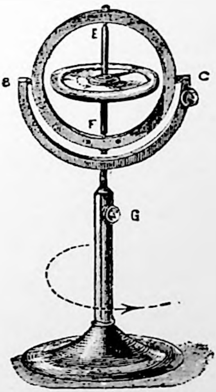


FIG. 2.—Gyroscope with spindle clamped at G. The axle of the wheel keeps parallel to the axis of rotation around which it revolves.

to the same spot in the room. If it was directed originally to the moon it will still point to the moon, if to the pole star it will remain so pointing and we would have the true north nearly. The rotation of the table seems to have no power to alter the direction initially given to the axle of the gyro-wheel. Stop the table, lift off the gyroscope and clamp the vertical spindle at G (fig. 2), thus suppressing one if its movements ; it has now only two degrees of freedom (1) on its axis E F ; (2) on the gimbals B C. Replace it anywhere

on the stationary table, nothing happens, the axle continues to point in the direction first given to it. But start spinning the table, and the axle of the gyro will stand vertical and will remain parallel to the axis around which the table is turning, and the axle of the wheel will always take up this position no matter in what direction it pointed to originally. The mere rotating of the table so influences the gyro-wheel that it endeavours to, and does, come to rest with its axle parallel to the axis of rotation. If the gyroscope were placed exactly on the centre of the table the two axes would be in the same vertical line.

The daily rotation of the earth from west to east is somewhat analogous to the turning of the table. Suppose the gyroscope to be on the earth's surface or standing on the deck of a ship at anchor, then it will be carried round the axis of the earth at the rate of one complete turn per day. If the gyroscope has two degrees of

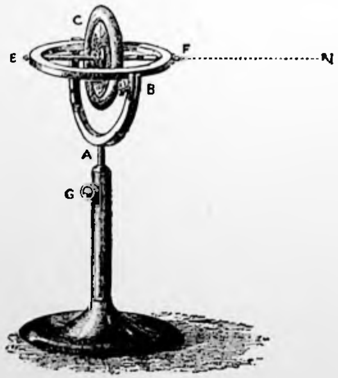


FIG. 3.—Gyroscope with ring clamped horizontally at B, but free to rotate on spindle. The axle of the wheel finds the north point of the horizon.

freedom as in fig. 3 (1) about its axle $E\ F$, (2) about the vertical spindle A, but the ring clamped in the horizontal plane at B, then the axle will find the true meridian and will oscillate slowly about the true north point of the horizon. Having now found the north and without moving the gyroscope, clamp the vertical spindle at G

and free the ring so that the wheel has still two degrees of freedom but this time (1) about its axle $E\ F$; (2) about the gimbals $B\ C$. The north end of the axle will now tilt up and point to the pole star as in fig. 1 and it will always take up this direction from every position on the globe (fig. 4).

The axle of the spinning wheel responds to the earth's dynamical force in much the same way as a freely suspended needle comes tc rest in the line of dip in obedience to the earth's magnetic force. This natural phenomena has been discovered and demonstrated, and ingeniously adapted to man's requirements. It should be assumed in accepting these remarks, that the gyroscope used is an ideal instrument, working perfectly and smoothly in all its parts and absolutely free from friction at all pivotal points.

THE EARTH SURROUNDED BY ROTATING WHEELS AS IT APPEARS TO AN IMAGINARY OBSERVER LOOKING AT IT FROM THE SIDE.

FIG. 4.

In the gyro-compass, as in the magnetic compass, only the horizontal component of the directional property is utilised, so the instruments have at least this in common that both are most effective in equatorial regions, and their value as direction finders gradually diminishes to a zero value as the latitude increases, the needle being useless at the magnetic pole and the gyro at the geographical pole. But the method of poising, pendulating and mounting the gyro-wheel so that it may function accurately on board

a lurching ship calls for scientific knowledge and mechanical skill of the highest order. The part in a gyro-compass corresponding to the ring in a simple gyroscope, for example, is not gimballed as in fig. 3, but the earth's gravitational force, as well as her rotational velocity, is ingeniously made to work in keeping the axle in a plane parallel to the earth's surface.

The three gyro-compasses on the market, named in the order they have emerged, are Anschutz (German), Sperry (American), Brown (British). The underlying principles are the same in each, but the mechanical devices introduced in order to adapt the fundamental laws to the purposes of navigation differ somewhat in character. The Anschutz has three gyro wheels each 5 inches in diameter and weighing 5 lbs., placed at each corner of an equilateral triangle and making about 20,000 revolutions per minute. The Sperry compass is fitted with a single wheel 10 inches in diameter, 2 inches wide, weighing 55 lbs. and is driven at a speed of 6000 revolutions per minute (figs. 6, 7 and 8). The Brown has one wheel 4 ins. in diameter and 4½ lbs. in weight, mounted centrally in the moving system and making 15,000 revolutions per minute.

Briefly, the installation consists of a master compass placed near the ship's centre of gravity, and repeater compasses mounted wherever required (fig. 5). A repeater compass may be laid face

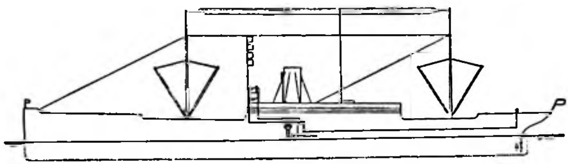


FIG. 5.—The master compass near ship's centre of gravity.

down or face up, or be hung up vertically on a bulkhead, and its portability is only limited by the length of the flexible cable connecting it to the distribution box of the compass installation. The ship's electrical current is converted into three phase alternating current of the proper characteristic to spin the gyros, then by means of an ingenious system of electrical contacts, auxiliary motors and geared mechanism the movements of the ship's head relatively to the axle of the master compass is communicated to the repeaters in a manner not unlike the synchronous working of electric clocks.

For information regarding the constructional features of the several types the reader is referred to the publications of their inventors and makers, Anschutz & Co., Kiel; the Sperry Gyroscope Co., Ltd., London; Messrs. S. G. Brown, Ltd., London; also to *The Gyroscope Compass*, by T. W. Chalmers, B.Sc. (The Engineers Series). The figures in this note have been reproduced, by permission, from the publications of the Sperry Gyroscope Company, and from a charming book on gyroscopic motion entitled *Spinning Tops*, by Professor J. Perry, D.Sc., F.R.S. (Romance of Science Series.)

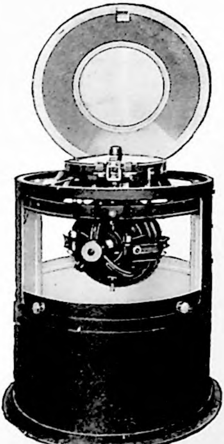
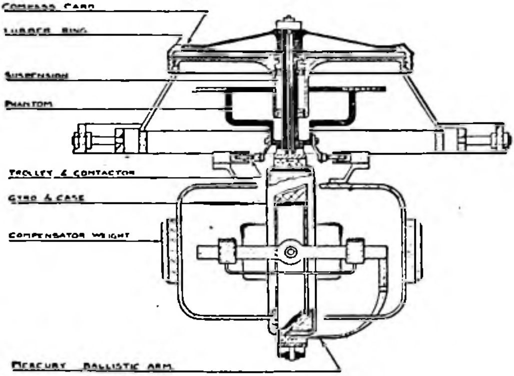


Fig. 6.—Master Gyro-compass

The navigator, however, is more immediately concerned with the application of the invention to his particular business, its manipulation and maintenance, its reliability and accuracy. Starting up is simplicity itself. Close the two pole switch which admits the ship's current into the compass installation, turn the handle of the starter and the whole plant is put into service. It takes the spinning wheels some time to get up speed and the axle takes a much longer time to settle in the true meridian, but the compass will be steady enough for steering purposes in a couple of hours and for accurate observation in from three to four hours. This period may

be reduced by gently steadying by hand the card of the master compass on north and south, but this should only be resorted to in cases of urgency.

The master compass is well protected, securely locked and is inaccessible to unauthorised persons. The installation should be inspected daily by the responsible navigating officer and the repeaters checked with the master compass to see that they synchronise. The pivotal bearings are oiled sparingly and not oftener than once a week. The motor generator and electrical controls require the ordinary care given to dynamos or motors.



CAST ELEVATION
FIG. 7.

The likelihood of failure depends chiefly on the reliability of the ship's electric plant, but in the event of anything going wrong with the compass an alarm is automatically sounded. The wheels, however, owing to their momentum, continue to spin for an hour or two after the current is cut off, so the master compass continues to function for some time and can be switched on to the storage battery, which is carried as a standby, until the defect is remedied. An adjusted magnetic compass will of necessity be carried to meet the remote contingency of the gyro-compass failing, just as oil lamps are still carried in case the electric light fails, and hand gear to replace a breakdown of the steam steering engine.

The accuracy of the compass is, and must be, determined by the navigator from time to time and this is done by sun and star azimuths in the usual way. There is no difference in this operation. Assuming then that the gyro-compass is working with the degree of accuracy claimed for it there should never be more than a single error of + or -2°, which, note, is constant for every direction of the ship's head and is either plus or minus on all courses; there are no

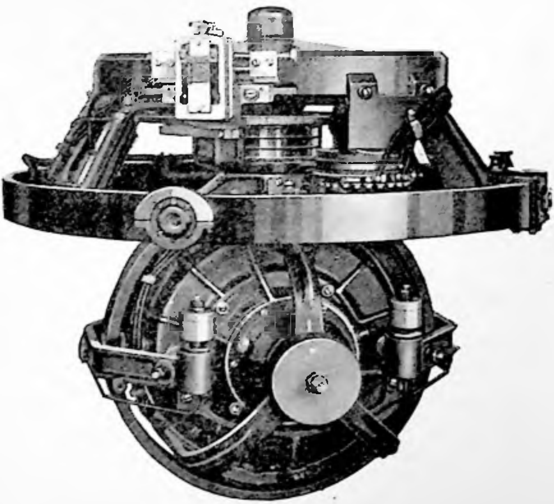
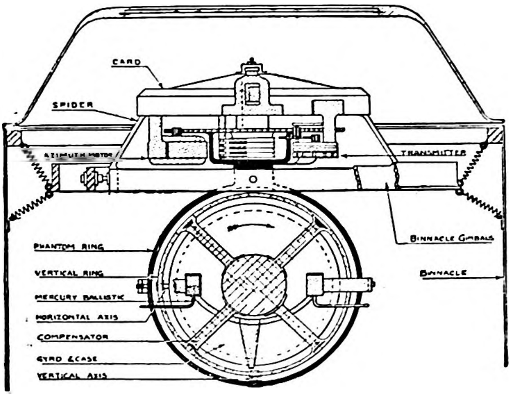


FIG. 8.
Complete Compass removed from Binnacle, Aft View of Spider, North View of Gyro.

distinctive quadrants, the card being graduated from north clockwise to 359° like the true circle of the new pattern compass printed on Admiralty charts.

The gyro-compass will only point steadily to the north when the axle of the wheel is perfectly level, and the primary object in view is to so mount and pendulate the system that the axle will keep rigidly in the horizontal plane. This is accomplished, partially, by keeping the centre of gravity of the system slightly below the plane of the gimbals *B C* instead of tightening the clamp screw at *B* as in

fig. 3. But if, from any cause whatever, the axle should tilt up it will precess, and in a frictionless gyro this precessional motion would continue indefinitely unless the oscillations were in some way automatically damped. Precession is all important in gyroscopic motion, and referring again to a running wheel as shown in fig. 10. we observe that the north end of the axle turns to the left hand when it is depressed below the plane of the horizon, and to the right hand when the north end points upwards.



NORTH ELEVATION.
FIG. 9.

A compound gyroscope functions in a similar way to the wheel, but, of course, it is not in contact with the ground, and the nature of its mountings limits the angle of deflection. The precessional motion of a gyro causes the end of the axle to describe a right-handed circular path of gradually diminishing radius. If the axle $E\ F$ (fig. 11,) were extended, and the north end were the point of a pencil in contact with a vertical sheet of paper, the pencil would trace out a spiral curve as shown in the figure, the point being somewhere above the line when precessing to the east, and below it when precessing to the west, but eventually, when the axle had found the north, the pencil point would come to rest at N. If the rotation of the spinning

wheel had been counter-clockwise when viewed from the south the axle would have traced out a left-handed spiral curve.

To encourage the axle of the gyro-compass to find the north as quickly as possible its precessional oscillations are suppressed, not by a rubbing friction, however, as the object aimed at in designing the instrument is to reduce frictional resistance to a minimum at all points of contact, but by getting the compass itself to automatically, and instantly, bring to bear on the axle a force equal and opposite to that which may be impressed upon it by some external influence. This counter-precessional tendency is effected by means of liquid in cisterns, oil in the Anschutz and Brown compasses, and mercury in the latest design of the Sperry compass, the containers being so placed and mounted as to balance each other when the axle is

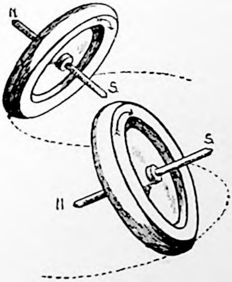


FIG. 10.

horizontal. When the axle tilts the oil flows from one cistern to the other, the quantity and rapidity of the flow being regulated by the inclination of the axle, the excess weight of oil, or mercury being distributed so as to cause the compass to precess in a direction in opposition to that due to the disturbing force acting upon it.

The sensitive element of the gyro-compass comprises a spinning wheel, axle, supporting rings, connections, etc., and weighs 15 lbs., 55 lbs., and 4½ lbs. in the Anschutz, Sperry, and Brown compasses respectively, in contrast with which, it might be remarked, the well-known Kelvin magnetic card weighs only about quarter of an ounce. The vertical support of this sensitive element must be entirely free from friction and of a most refined character, otherwise it is doubtful if the relatively small directive force generated by the spinning

wheel would be sufficiently strong to enable the moving system to seek out and find the meridian or to manifest a compass action. The Anschutz compass floats in a bowl of mercury; the Sperry is suspended by means of a torsionless steel wire, but the most ingenious central axis of all is the hydraulic support introduced in the Brown compass. The lower end of the vertical spindle acts as a ram and stands upon a column of oil. The oil is under great pressure, some 500 lbs. per square inch, and is kept pumping up and down, thus raising and lowering the vertical axis continually some 180

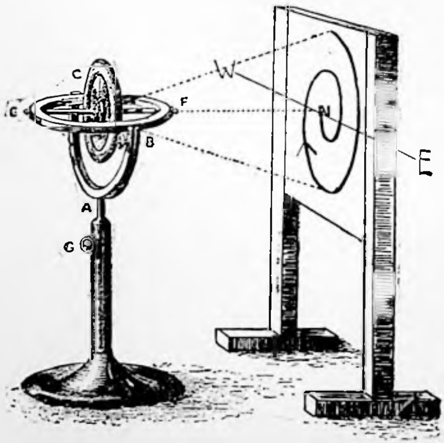


FIG. 11.

times every minute. The vertical vibratory impulse is about $\frac{1}{8}$ of an inch, and before the foot of the spindle falls on the bottom of its bearing it gets another kick up by the pulsating oil so that no actual metal to metal contact is established. This is considered to be the most perfect frictionless support yet given to the vertical spindle of any machine.

The gyro-compass is subject to three errors, latitude error, ballistic deflection, and steaming error. The first two are entirely dependent on the design of the instrument, but the steaming error is the same for all types. Fortunately, all these errors can be almost eliminated by mechanical compensation; nevertheless a short

discussion of each may, perhaps, be a good way of conveying a general notion of the action of the spinning compass.

It has already been remarked that a gyro axle endeavours to point to the pole star. It would therefore be a comparatively simple matter to design an instrument to function as a compass at a place on the equator, for then the pole star is on the horizon and consequently the natural position of the axle would be to lie in the horizontal plane. But the elevation of the pole increases with the latitude so that at Glasgow in 56° north the axle would be tilted at an angle of 56° above the horizon, and at the geographical pole it would stand upright as the object of its adoration would then be overhead. Now, the gyro-compass is forcibly prevented from acquiring the

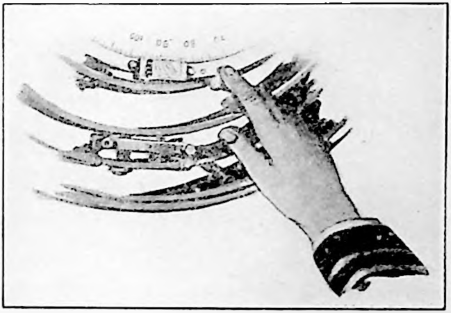


FIG. 12.—Turning the Adjusting Screw to Correct for Change of Latitude.

natural tilt of its desire by pendulously suspending the sensitive element, thus coercing the axle by mechanical means to lie in the horizontal plane. This, however, introduces an error which increases progressively with the latitude of the ship, the amount depending on the design of the compass and the system of damping device adopted to get the axle to settle as quickly as possible in the plane of the true meridian. Fortunately, all types are designed to automatically compensate for latitude error, thus relieving the navigator from the necessity of applying a correction, the adjustment in the Sperry being made by simply turning a screw as indicated on a scale attached

to the compass whenever the change of latitude is large enough, every 10° or so, to make the error appreciable,

This same screw may also be used, if desired, to correct the steaming error which depends on the ship's course, her speed and her latitude, and is an error common to all gyroscopic compasses It is a natural deflection of the compass north from the true north and is tabulated for every degree of ship's head, for a wide range of speeds and every 10° of latitude. The error is maximum when steaming north and south, its value gradually diminishing as the ship's head approaches east and west, when it vanishes. For

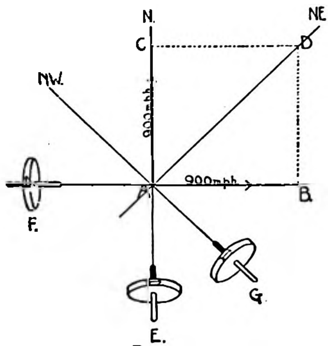


FIG. 13.

E, Position of Axle if influenced by the Earth's Rotation only.
F, Position of Axle if influenced by North-going Speed of the Ship only.
G, its Position when influenced equally by the Earth and Ship combined.

example, lat. 0°, head N., the error is 0·6° at 10 knots, and 1·3° at 20 knots; in lat. 50°, head N., it is 1·0° at 10 knots, and 2·00° at 20 knots. This error is minus on northerly courses and plus on southerly.

In the Sperry compass the manipulation of the screw referred to compensates for both latitude and steaming errors; in the Brown installation the repeater compasses are designed so that the steaming error may be allowed for by an eccentricity of the card and, when once set, the correction is automatically applied, and only in the Anschutz is the steaming error taken from the tables and applied arithmetically like a deviation.

A discussion of the steaming error demonstrates very clearly the sensitiveness of a gyro-compass in seeking to align the axle of the spinning wheel parallel to the axis of rotation acting upon it. On land this would be the axis of the earth which does not change, but on a moving ship the new axis of rotation is at right angles to a path which is the resultant of the ship's directional velocity combined with that of the earth's rotational velocity. When looked at side on from the south the gyro-wheel spins clockwise and its axle points north and south (fig. 6). At the equator, if the ship were stopped, the compass would be carried round the earth's axis from west to east at the same velocity as a place on shore, the rate being $15^\circ \times 60$ mls. $=900$ miles per hour. If the ship now steams east at 10 knots the compass will be rotated round the earth's axis at 910 m.p.h., and if she steams west the rotational velocity will be reduced to 890 m.p.h. Mere translation to the E. or W. does not alter the direction of the axis around which the compass rotates, the axle still points to the pole and keeps parallel to the axis of the earth.

But if, on the other hand, the earth ceased to rotate and the ship steamed round the globe, through the poles, and made a complete circuit of the earth in a day, then the compass would be carried round a new axis lying at right angles to the earth's axis, and the axle of the gyro-wheel would point to the west. If the earth's rotation be now restored the gyro would be acted upon equally by the influences of the earth and ship combined and would point N.W., because the ship in this case would be carrying the compass to the north (D. lat.) at the same speed as the earth is carrying it to the east (dep.) at the equator.

Suppose, however, the ship steams north, 10 knots, this is equivalent to a difference of latitude, and the 900′ of easting due to the earth is equivalent to departure. Diff. lat. 10 m.p.h. and dep. 900 m.p.h. gives a course of N. 89·2° E., so that the wheel is carried along a line in space parallel to $A\ D$ (fig. 14), it would turn its axle into line with $A\ E$ at right angles to its path $A\ D$, and angle $N\ A\ E$ would be 0·8°. If the speed were now increased to 20 knots, then diff. lat. 20 m.p.h., dep. 900 m.p.h., would increase the angle $N\ A\ E$ to 1·3°.

Consider now the case of a ship in any other latitude—say 60° for easy reckoning as the earth's rotational velocity on this parallel is exactly 450 m.p.h., half the equatorial speed—then, when steaming north, 10 knots, diff. lat. 10 m.p.h., dep. 450 m.p.h., the angle $N\ A\ E$

$=1 \cdot 3°$, and at 20 knots it would be $2 \cdot 5°$. In these respective cases the compass north would point $1 \cdot 3°$ and $2 \cdot 5°$ to the left of true north. It is evident, therefore, that the latitude as well as the north and south speed of the ship affects the compass, and, obviously, the speed at which she changes her latitude depends on the direction she is heading, thus the three variables are course, speed and latitude.

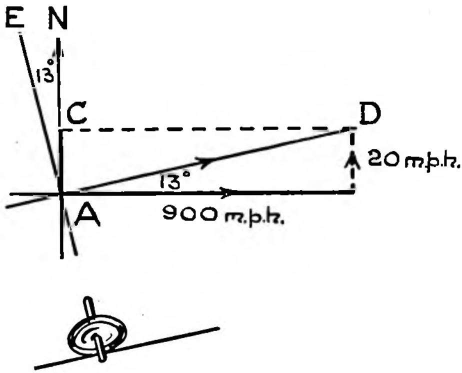


FIG. 14.

A C. the North-going Speed of the Ship.
A B, the East-going Speed of the Earth.
A D, the Resultant Velocity and Direction along which the Gyro-compass is impelled.
A E. the Direction in which the Gyro Axle points.

The gyro-compass when started up wanders with an exasperatingly slow deliberation. It takes about a couple of hours to find the north near enough for steering purposes and an hour or two longer for accurate observations. A period of about 85 minutes has been purposely chosen for all gyro-compasses in order to get the two errors, steaming error and ballistic deflection, to partially counteract each other. The sensitive element acts like a horizontal pendulum, the axle of the spinning wheel pointing north, and so long as the ship is steaming at a steady speed to the N. or S. the compass is not affected. But if she increases, or decreases, speed, or stops suddenly, the whole pendulated system receives a jolt, due to the action of its

own inertia, causing the axle to tilt and consequently to oscillate. Have you ever stood in a crowded tramway car and tried to preserve a dignified appearance of equilibrium under the influence of its frequent accelerations and decelerations of speed? Now, just sit down and quietly study for a moment the motions of a pendulum suspended from the roof of the car. When the car is moving forward at a uniform speed the pendulum, when at rest, takes up a mean position. If the pendulum be now swung in a fore and aft direction it will be noted that the plumb bob swings an equal distance in front of, and behind, its mean position so long as the car continues to go smoothly forward at a steady uniform speed. But if the speed of the car is quickly accelerated the bob of the pendulum lags behind at first, then gradually adjusts itself to a new mean position, which depends on the new speed. And if the car is suddenly pulled up the bob swings violently forward and oscillates irregularly before it finally comes to rest.

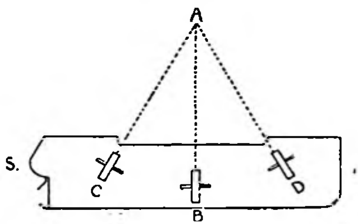


FIG. 15.

Suppose in fig. 15 *A B* to be the position of rest of our pendulous gyro-compass when attuned to the speed of the ship which we will assume to be going north, then, when the ship's speed is increased, the pendulated system will tend to lag behind and to take up a position as at *C*. Of course, the compass itself does not move aft—it is suspended in a binnacle and fixed to the deck—it has merely a tendency to do so—but the axle of the gyro actually tilts as shown in the figure, and as it tilts it begins to precess, or wander, with the right-handed circulatory movement already described in fig. 11.

If the ship is steaming north, say at 20 knots, and her speed is suddenly reduced, the compass receives a jolt and is pitched forward owing to the momentum imparted to it by the ship's former speed. In this case the compass, instead of moving forward to position *D*,

tilts up its north end in an effort to preserve its equilibrium, and oscillates around the north point of the horizon until the pendulous system adjusts itself to the new speed. The consequent precession is called the ballistic deflection, and, as it acts in opposition to the precession due to the north steaming error, the desirability of designing the instrument so that the two opposing errors may neutralise each other for some particular position is evident. Latitude 50° N. has been selected for this purpose, but a precise balance between the two errors cannot be maintained for all conditions, and, so far, the best results have been obtained with compasses having a period of 85 minutes. Variations in the course and speed of a merchant ship are, however, usually made in a leisurely manner so that ballistic deflection, even if it were not automatically compensated, causes but little inconvenience.

The question of period has some rather interesting applications in navigation. The period of an ocean wave of 500 to 600 feet long is about 10 seconds; that is the time elapsed between the passing of two successive crests over a fixed point. The period of a complete roll of a large beamy steamer depends on her metacentric height, but averages usually about 15 seconds, although it may be longer in a comfortable passenger ship, as, amongst other things, the naval architect aims at designing a ship to have a slow period of roll under average sea-going conditions. The Kelvin compass card is designed to have a period of about 33 seconds so that the natural swing of the card may not synchronise with the roll of the ship. The period of a clock pendulum is, of course, one second, and gives a tick every half second. If we wish the clock to go slower we lengthen the pendulum by lowering the bob, because the time of the swing is proportional to the square root of its length. If it were possible to make a simple pendulum equal in length to the radius of the earth—about 4000 miles—the clock would tick, not every half second, but once every three-quarters of an hour, the period of oscillation being now increased from one second to about 85 minutes. An undamped gyro-compass when started up would take this period of time to swing from right to left and back again to the right, and it would continue to do so indefinitely until brought to rest by friction, hence the necessity for retarding its oscillations so that the compass may find the north within a reasonable time.

In our remarks we have tried to focus the reader's attention on the necessity of keeping the axle of the gyro level, and this could be

accomplished by quite a simple form of gyro-compass on shore where it is acted upon by the earth's rotation only. The spinning wheel, however, responds to the resultant effect of all the various forces acting upon it. When we have experienced, physically, the severity of the rolling and pitching of a lively ship and remember that her every movement tends to tilt the axle, we cannot fail to be impressed with the fact that a ship is far from being an ideal place to

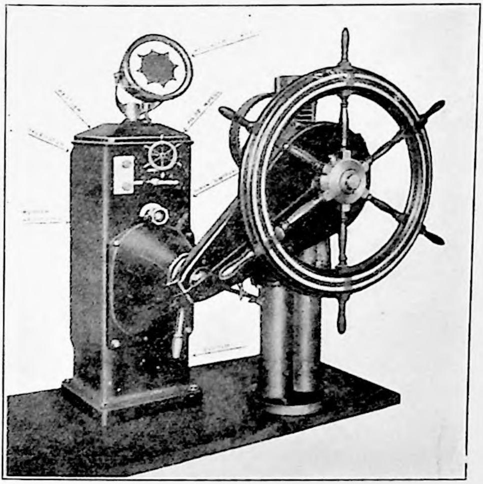


FIG. 16.—Gyro-Pilot connected to steering wheel.

get a gyrostat to act as a compass. Much credit is, therefore, due to the inventors and makers of the nautical gyro-compass for their perseverance and ingenuity in successfully designing an instrument insensible to the movements of the ship and responsive only to the slow angular rotation of the earth.

The navigational utility of the gyro-compass is not limited to its directional properties only, as evidenced by the Sperry recording compass. This auxiliary instrument follows the movements of the master compass and traces on a diagram the courses steered and the steaming time on each as in fig. 18.

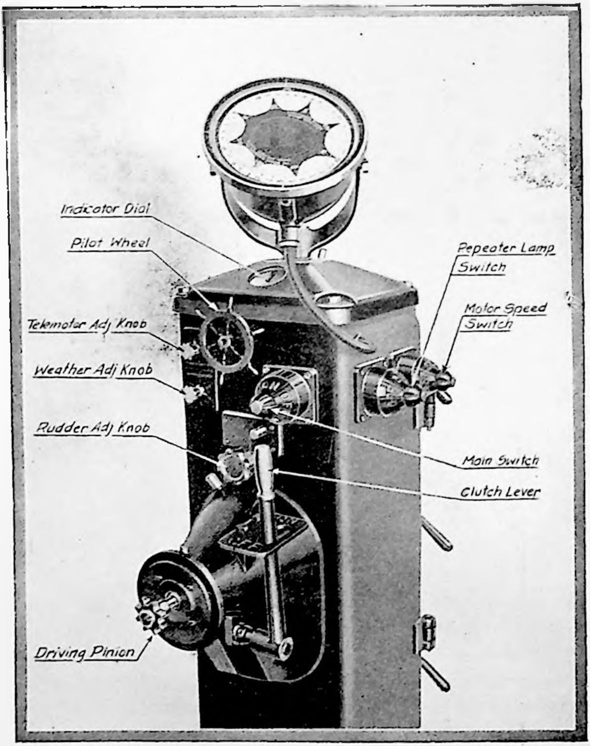


FIG. 17.—Description of Units of the Gyro-pilot.

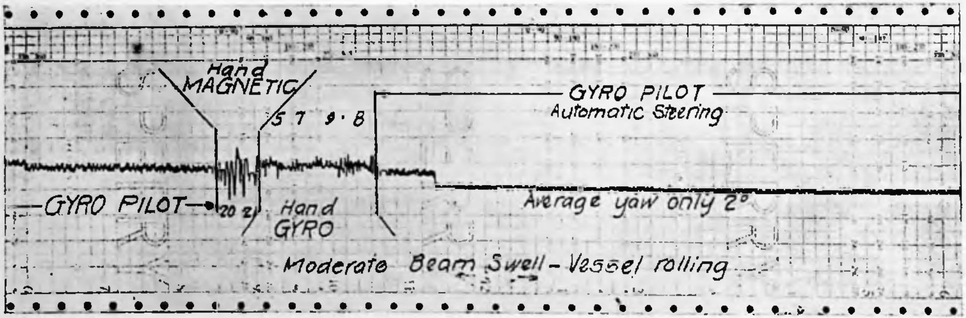


FIG. 18.—Course Records made by the Sperry Automatic Course Recorder

A self-steering compass has been designed by the Sperry Company which is in mechanical connection with the steering wheel of the rudder engine. The ship is steadied on the desired course as indicated by the master compass, the self-steering compass is then set to this course, the electrical contact switched on and a lever turned from hand-steering to self-steering. When the ship is on her course nothing moves, but when she yaws the steering engine is operated, less or more, according to whether the ship is slightly, or considerably, off her course. A small wheel operated by hand enables changes in the course to be made and also way-giving manoeuvres.

Perhaps a few direct questions and answers may help to draw attention to some of the features of the gyro-compass.

1. What is the principle of the gyro compass?

The working of the gyro compass depends on the gyroscopic law that a fast spinning wheel when mounted so as to move simultaneously with freedom in every plane keeps its axle parallel to the direction initially given to it. This direction is called its "rigidity in space." To be of use as a compass on board ship, however, the gyro wheel must find the true north and remain rigidly in the true meridian. This is effected by mounting the wheel in such a manner that when it is spinning, and in equilibrium, the axle automatically comes to rest in the horizontal plane. The axle is then pointing true north. (pp. 216 to 221.)

2. What is meant by "precession?"

When the gyro axle finds the north it is exactly horizontal. If the north end of the axle be now forcibly depressed and then released, it wanders slowly to the westward of north, then back to the eastward of north, tracing out a clockwise spiral curve of gradually diminishing radius until it comes to rest pointing north again. This turning movement is called precession, and the motion is always at right angles to the direction of the impressed force. Imagine a wheel having clockwise rotation when viewed from the south, then, if the north end of the axle be depressed the whole mass of the wheel turns horizontally to the left hand; if the north end of the axle be raised the north end turns to the right hand. When the axle is pushed sideways it refuses to go horizontally but moves vertically upwards or downwards. (pp. 218–220.)

3. Explain what is meant by "three degrees of freedom" and state how they are embodied in a gyro compass.

The three degrees of freedom of an elementary gyroscope are:—
(1) Freedom for the wheel to spin on its axis.
(2) Freedom to rotate about the vertical axis.
(3) Freedom to rotate about the horizontal axis.

In the Sperry gyro compass these are embodied as follows:—(1) The wheel is electrically rotated at about 6000 revolutions per minute. (2) The whole element is suspended vertically by a torsionless steel wire. (3) The horizontal movement, however, is partially suppressed and its meridian seeking properties are obtained by causing mercury to flow between boxes on the north and south sides of the gyro when the gyro is tilted. In this form of ballistic the gyro wheel is rotated counter clockwise when looked at from the south. (pp. 218–228.)

4. What is the natural period of oscillation of the gyro compass wheel?

A period of 85 minutes which corresponds to the period of a vertical pendulum the same length as the earth's radius, about 4000 miles. (p. 232.)

5. Name the principal parts of the master gyro compass.

The sensitive element of the master compass consists of a rotor or gyro wheel enclosed in a casing mounted within a vertical ring. The rotor in the Sperry is a forged steel flywheel 12 inches in diameter and 2 inches thick. A squirrel cage armature is fitted in the centre, and a steel shaft is fitted securely through the boss of the rotor.

The vertical ring which carries the sensitive element is held in suspension within another ring called the "phantom," and the direction of the axle, that is the shaft of the rotor, is communicated to a compass card mounted within a spider band above the casing of the rotor.

The master compass is housed in a binnacle inside the ship, the nearer to her centre of gravity the better. Repeaters are operated electrically from the master compass through a transmitter and a pinion mashing with a circular rack on the phantom. Repeaters may be fitted in any number and in any position throughout the ship. (Figs. 7, 8, 9.)

6. When is a gyro wheel statically unbalanced and dynamically unbalanced?

It is obvious that the whole combination of wheel within rings must be perfectly balanced; for example, the centre of gravity of the rotor must be exactly on its spinning axis; if not, then it is said to be statically unbalanced.

The spinning axis must be exactly perpendicular to the plane of the rotor, otherwise it is said to be dynamically unbalanced and in both cases if not perfectly balanced vibration will be set up. Furthermore, the rotor casing, regarded as one unit, must also be balanced both horizontally and vertically. Special apparatus is required to ensure that rotors are statically and dynamically balanced and any defects are eliminated at the works.

7. Describe how a gyro compass is started.

Assuming the electrical parts of the equipment to be in order, I would steady the sensitive element by hand so that the bubbles of the levels are centralised when the compass is set approximately to the direction of ship's head; set the latitude levelling to the required latitude, then switch on the current and turn the motor generator switch slowly to the "on" position. The rotor will then start, and will be up to full speed in about one hour, which is 8600 r.p.m. (Sperry), 15,000 r.p.m. (Brown), 20,000 r.p.m. (Anschutz).

Disengage the casing clamp. The compass should have found the north point in about three hours and ready for navigation.

8. How is the speed of a fast spinning rotor registered?

The revolutions are registered by means of a "stroboscope." This instrument consists of a hand-driven disc geared to a counting mechanism. This disc has five equally spaced view holes round its edge and is enclosed in a metal case with a sighting hole on each side.

A spiral line is painted on the side of the rotor which can be seen through a window of the compass. When the rotor spins slowly the white spiral appears to travel across the window, but at high speeds it is just a blur. In taking the speed of the gyro the rate of turning the disc of the stroboscope is first adjusted until the spiral on the rotor when viewed through the sighting holes of the instrument appears at rest. Then the counting mechanism, already set at zero, is put into gear by pressing the button on the case.

Synchronism is maintained for half a minute by stop watch, the pressure on the button is then released to stop the action of the counting gear. The revolutions per half minute are read off from the scale.

9. What is the "settling point" of a gyro compass?

The settling point is the position of rest which the compass ultimately attains when the gyro axle does not move relatively to the north-south horizontal line.

The axis of a free gyroscope if pointed upwards towards a star will continue to point to that star throughout the day. If we were to imagine the axis extending into space it would trace out a path in the heavens coincident with the circumpolar path of the star towards which it points, and it would continue to precess indefinitely, that is, to follow the star, until brought to a standstill by friction or stoppage of the wheel. If the axis were directed to the North star it would keep pointing to this point in space.

To convert the gyroscope into a compass the axle is first pointed to the celestial pole and then coerced into lying in the horizontal plane, thus suppressing one of its degree of freedom; furthermore, its precessional activity has to be repressed, or damped, otherwise it would not come to a position of rest.

The method of damping differs in the several types of compasses: the principle, however, is the same in each, viz., a torque is applied to the axle so as to induce precession in a contrary direction. For example, if the north end of the axle is pushed upwards and begins to precess right handed, then a gentle downward pressure or weight applied to the north end will tend to produce a left-handed precession because a force so applied produces a movement about the horizontal axis tending to wipe out the tilt and so eliminating the cause of the oscillation.

When the axle of the compass is forcibly tilted the balance is instantly restored and the compass prevented from wandering by means of mercury or oil in two boxes, one on each side of the compass, and so placed that the excess of weight is automatically transferred from one box to the other, through communicating pipes, to bring pressure to bear on one end of the axle so as to cause a counter precession and thus keep the compass pointing in its settled position. (See Fig. 9.)

10. Does the compass point true north in latitude 50° N.?

No. The amount of error will depend upon the design of the instrument. In the Sperry compass, with counter clockwise rotation, the error would be $-2°$ in latitude 50° N., but $+2°$ in latitude 50° S.

11. Describe the errors of the gyro compass.

The errors are of two classes:

(1) Those that are inherent to all compasses the most important one being the speed error. This error may be calculated, tabulated and applied arithmetically to the compass course as in the case of the Anschutz, or mechanically in the Sperry and Brown systems by turning a small adjusting dial according to the course and speed of the ship.

(2) Those errors dependent on the design of the instrument; (*a*) the latitude error, (*b*) an error due to rapid alteration of ship's head or to sudden acceleration and deceleration of speed; these are ballistic errors.

(*a*) Latitude or damping error. The compass can be set correct for any desired latitude, but a gradual error creeps in on moving away from that latitude due to the tilting of the gyro axis which causes the axle to precess and to find another position of rest. This settling point may be a little to the east or west of north depending on whether the rotor spins counter clockwise or clockwise.

(*b*) Sudden increases or decreases of speed jolt the gyro, thus tilting the axle temporarily until it can again accommodate itself to the new speed.

Adjustments are made by means of a small dial which turns the lubber line of the Sperry master gyro through an angle equal to the correction, and this movement is passed on to the repeaters so that the repeater cards keep in step with the master compass. The Brown compass automatically corrects itself for latitude error.

12. What is meant by "ballistic deflection?"

The successful functioning of a gyro compass depends upon the accuracy with which it maintains its balance when the axle is exactly horizontal. Its balance, however, is disturbed by change of latitude, change of course and change of speed, the resulting error being called "ballistic deflection."

The latitude and speed errors act in opposition to each other and it is possible to balance the gyro compass for any desired latitude so that the latitude error will be equal and opposite to the speed error. The Sperry pendulous compass is balanced for latitude 40°. This compass is fitted with an automatic device which corrects for all errors by simply setting the latitude and speed dials.

13. Describe latitude error.

This error is a natural one common to all forms of gyro compasses and is caused by coercing the gyro wheel to keep horizontal, whereas it wants to keep parallel to the earth's axis, that is to say, pointing up to the pole star. The horizontal component only is wanted for the directional properties of a compass, so the north end of the axle is brought down to the horizontal plane, in consequence of which it takes up a position a little to the west of north in the North Hemisphere and a little to the east of north in the South Hemisphere. This error is greatest at the geographical pole, diminishing to zero at the equator.

14. What is damping error?

This error, sometimes called latitude error, appears in the Sperry system where a torque in the horizontal plane is introduced by the method adopted to damp the oscillations of the compass.

The eccentric pivot is fixed a little to one side of the vertical plane through the gyro axis, thus forming a lever about one-tenth of an inch in length, so that the pressure of the mercury control acting on the pivot produces the torque necessary to damp the compass but at the same time affects its settling point.

The damping error varies with the latitude and is given by the formula error in degrees = eccentricity in degrees × tan lat.

The error is compensated by hand by setting the "speed and latitude" dial to the latitude of the ship.

15. Describe speed error.

The speed error is due to the progressive motion of the ship. The axle points true north when under the influence of the earth's rotation only. When the ship gets under way the wheel wants to set its axle at right angles to the ship's track and the faster the ship goes the more eager is it to do so. The direction the axle actually

takes up is the resultant of the ship's directional velocity and the earth's rotational velocity. The maximum error appears on north and south courses, gradually decreasing to zero on east and west courses, but increases on each course with every increase of speed. The error is minus on northerly courses and plus on southerly courses.

The steaming error is due to natural causes and is the same for all gyro compasses. It is calculated from the following approximate formula:—

$$\text{Deviation} = \frac{\text{ship's speed} \times \cos.\ \text{course} \times \cdot 064}{\cos.\ \text{lat.}}$$

Example.—Find the deviation on a gyro compass in latitude 56° N., ship steaming N. 60° E. at 15 knots.

Dev. $= 15 \times \cos 60° \times \cdot 064 \div \cos 56°$

„ $= 15 \times \cdot 5 \times \cdot 064 \div \cdot 56° = \cdot 85°$ to subtract. (p. 238.)

16. Do the pitching and rolling of the ship affect the steadiness of the gyro compass?

The mercury ballistic compass is not affected by rolling and pitching as it is non-pendulous and the disturbing forces are adjusted to neutralise each other. The earlier types of the Sperry gyro compass, however, were pendulous, so that violent pitching of the ship sometimes gave the sensitive element a jolt which caused the axle to precess a little.

17. What is a "repeater" compass?

The steering, azimuth and other compasses placed wherever wanted in the ship are called repeaters. The master compass is the only gyro compass on board. A repeater is worked electrically off the master compass, the dial being turned by a relay motor so that it indicates the same direction as the master. It is, however, necessary to compare the repeaters with the master compass occasionally, and always on first starting up, to see that they all synchronise; if any of the repeaters do not indicate the same direction as the master compass they are made to do so by turning an adjusting screw.

18. How is the error of the gyro compass determined?

By means of sun and star azimuths, or from the known true bearings of distant objects, in the same way as for a magnetic compass, one of the repeaters called the azimuth repeater, being fitted with sight vanes for doing so. When at anchor, by sextant right and left horizontal angles for any three well defined objects taken at the azimuth repeater. The angle when laid off on the chart with a station pointer fixes the position of the repeater relatively to the objects. The bearing of each object is then lifted from the chart, and comparison made with their bearings by the repeater gives the error of the compass. The repeater should be checked at the same time with the master compass to ensure that they are in agreement.

19. What are the navigator's duties with regard to the care and maintenance of the gyro equipment?

(1) Inspect the master compass regularly to ensure that it is running smoothly and that the readings of the electrical instruments indicate normal current and working conditions.

(2) Keep the instrument clean by removing dust and dampness from contacts, relays, etc.

(3) Set the dials on the master compass for change of latitude and speed to the prevailing conditions.

(4) Check the accuracy of the compass by azimuths, and compare repeaters with the master compass.

(5) Oil the bearings sparingly once a week.

(6) Every six months the whole outfit should be specially examined, and spare parts utilised if required.

20. State some of the advantages and disadvantages of the gyro compass.

It indicates true north and there is no troublesome deviation to contend with.

Its directive force is about 400 times greater than the magnetic compass and it holds to the true north with great rigidity.

It is unaffected by change of cargo, or of trim, or the rolling and pitching of the ship.

The error, if any, is small and is a constant plus or minus on all headings which can be adjusted by turning a screw:

It has a reserve of power by which auxiliary instruments can be operated to keep in step with the master compass, such as the course recorded and the automatic steering apparatus.

It simplifies navigation and thereby contributes to safety at sea.

The only disadvantage as compared with the magnetic compass seems to be the initial cost of the gyro compass and the small expense in connection with its care and maintenance.

APPENDIX

TABLE I.

Natural Sines and Tangents.

Degrees.	Chord.	Sine.	Tangent.	Co-tangent.	Cosine.		
0°	0	0	0	∞	1	1·414	90°
1	·017	·0175	·0175	57·2900	·9998	1·402	89
2	·035	·0349	·0349	28·6363	·9994	1·389	88
3	·052	·0523	·0524	19·0811	·9986	1·377	87
4	·070	·0698	·0699	14·3007	·9976	1·364	86
5	·087	·0872	·0875	11·4301	·9962	1·351	85
6	·105	·1045	·1051	9·5144	·9945	1·338	84
7	·122	·1219	·1228	8·1443	·9925	1·325	83
8	·140	·1392	·1405	7·1154	·9903	1·312	82
9	·157	·1564	·1584	6·3138	·9877	1·299	81
10	·174	·1736	·1763	5·6713	·9848	1·286	80
11	·192	·1908	·1944	5·1446	·9816	1·272	79
12	·209	·2079	·2126	4·7046	·9781	1·259	78
13	·226	·2250	·2309	4·3315	·9744	1·245	77
14	·244	·2419	·2493	4·0108	·9703	1·231	76
15	·261	·2588	·2679	3·7321	·9659	1·218	75
16	·278	·2756	·2867	3·4874	·9613	1·204	74
17	·296	·2924	·3057	3·2709	·9563	1·190	73
18	·313	·3090	·3249	3·0777	·9511	1·176	72
19	·330	·3256	·3443	2·9042	·9455	1·161	71
20	·347	·3420	·3640	2·7475	·9397	1·147	70
21	·364	·3584	·3839	2·6051	·9336	1·133	69
22	·382	·3746	·4040	2·4751	·9272	1·118	68
23	·399	·3907	·4245	2·3559	·9205	1·104	67
24	·416	·4067	·4452	2·2460	·9135	1·089	66
25	·433	·4226	·4663	2·1445	·9063	1·075	65
26	·450	·4384	·4877	2·0503	·8988	1·060	64
27	·467	·4540	·5095	1·9626	·8910	1·045	63
28	·484	·4695	·5317	1·8807	·8829	1·030	62
29	·501	·4848	·5543	1·8040	·8746	1·015	61
30	·518	·5000	·5774	1·7321	·8660	1·000	60
31	·534	·5150	·6009	1·6643	·8572	·985	59
32	·551	·5299	·6249	1·6003	·8480	·970	58
33	·568	·5446	·6494	1·5399	·8387	·954	57
34	·585	·5592	·6745	1·4826	·8290	·939	56
35	·601	·5736	·7002	1·4281	·8192	·923	55
36	·618	·5878	·7265	1·3764	·8090	·908	54
37	·635	·6018	·7536	1·3270	·7986	·892	53
38	·651	·6157	·7813	1·2799	·7880	·877	52
39	·668	·6293	·8098	1·2349	·7771	·861	51
40	·684	·6428	·8391	1·1918	·7660	·845	50
41	·700	·6561	·8693	1·1504	·7547	·829	49
42	·717	·6691	·9004	1·1106	·7431	·813	48
43	·733	·6820	·9325	1·0724	·7314	·797	47
44	·749	·6947	·9657	1·0355	·7193	·781	46
45°	·765	·7071	1·0000	1·0000	·7071	·765	45°
		Cosine	Co-tangent	Tangent	Sine	Chord	Degrees

TABLE II.

Latitude North. Degrees.		Sidereal Time. 0h.	1h.	2h.	3h.	4h.	5h.	6h.	7h.	8h.	9h.	10h.	11h.	Latitude North. Degrees.
0	E.	2.14.1.	2.3.14.1.	2.4.5.15.10.	16.4.5.15.	18.15.	17.18.6.	17.6.7.	17.7.	19.20.7.	9.19.20.	21.9.22.8 7.	21.19.8.	0
	W.	11.24.	11.24.		12.	12.13.	13.	13.		2.	2.1.14.15.	14.15.3.2.	15.16.17.4	
10	E.	2.14.1.13.	2.3.14.13.	16.3.4.2.5.	17.15.5.4.	15.	18.15.6.7.	7 6.15.18.	7.17.	17.20.8.7.	7.9 20.19.	19.22.9.8.	19.21 22.	10
	W.	10.11.	11.	13.	12.13.	12.13.	13.		15.	16.2.1.	1.14.16.	2.15.14.	3.16.	
20	E.	13.2.1.	13.14.3.2.	16.4.	16.5.4.	7.15.	15.18.16 7.	15.7.6.	7.8.	8.	9.20.	22.9.	2[illegible].	20
	W.	10 11.	11.	13.	13.	12.			15.	15.	1.15.14.	2.3.14.	2.3.16.	
30	E.	1.2.	3.4.14.	3.4.14.16.	16.5.7.	7.15.	6 18.7.	16.6.18.	8.	8 9.	9.20.	9.20.	22.	30
	W.	10.11.	10.11.		12.	12.			15.	14.1.	1.14.16.	2 16.3.	2.16.3.	
40	E.	1.3.	4.3.14.	4.3.14.5.	7.5.4.	5.7.16.	6.8 16.	18.6.8	8.18.	8.	9 20.	9.20.	22.20.	40
	W.	10.11.	10.11.	10.	12.	12	12.	14.	18.14.	16.14.1.	16.14.3.1.	16.3.1.	2.3.5.	
50	E.	4.1.7.	4.3.7.	4.3.7.14.	14.5.7.	16.5.14.	16.14.6.8.	16.8.6.18.	18.8.	9.18.	18.9.	20.10.9.	10.20	50
	W.	10.8.11.	10.11.	10.	10.12.	12.	12.	14.	10.14.	16.14.1.	10.11.2.1.	1.3.16.5.	2.3.5.18.	
60	E.	1.4.7.	1.3.4.7.	3.4.8.	14.5.3.8.	14.5.6.8.	14.5.6.8.	16.5.18.6.	9.10.18 6.	9.10.18.	10.9.18.	10.9.20.	10.20.	60
	W.	10.11.	10.11.	10.12.	10.12.	10.12.	10.12.	10.14.	10.14.	14.16 3.1.	16.3.5.1.	5.3.1.18	3.5.18.1.	

Latitude North. Degrees.		Sidereal Time. 12h.	13h.	14h.	15h.	16h.	17h.	18h.	19h.	20h.	21h.	22h.	23h.	Latitude North. Degrees.
0	E.	21.19.23	21.23.	10.21.	11.10.	24.11.	24.	21.12.	12.24.	24.	13.	13.	1.13.	0
	W.	17.16.7.4.	7.18.	7.18.19.6.	7.6.19.21.	19.21.8.	20.21.8.9.	21.9.20.8.	9.21.22.	22.23.	23.24.10.	10.24.	10.24.	
10	E.	22.23.	21.10.23.	21.10.	10.11.	11.	24.	12.24.	12.24.	21.		13.	13.1.	10
	W.	4.5.	19.18.7.	19.6.7.	21.19.7.	21.7.	21.20.8.	20.8.21.	9.22.8.	23.	24.23.	24.10.	24.10.	
20	E.	23	10.23.21.	10.21.23.	11.	11.		12.	12.24.				1.2.	20
	W.	4.5.	18.4.5.	6.18.	21.6.7.	7.21.	7.20.	20.7.8.9.	9.8.22.	8.9.23.	24.	24.	10.	
30	E.	10.22	10.23.	10.23.	11.23.	11.	12.	12.	12.			2	2.1.	30
	W.	2.5.4.	4.5.18.	4.6.18	6.	20.7.	20.7.	9.7.20.23.	9.8.22.3.	9.8.23.	8.		10.11.	
40	E.	22.10.	10.23.22.	23.10.22.	11.23.	11.23.	12.	12.	12.		2.	2.	1.2.	40
	W.	2.4 5.18.	2.4.5.18.	4.6.18.	6.	20.22.	20.22.23.	22.23.20.9.	9.7.23.8.	9.7.8.	7.8.	7.8.	10.11.	
50	E.	10.20.24.	20 22 10.	22.	23.11.	23.11.	12.11.	12.2.	2.12.	2.	2.	2.1.	2.1.7.	50
	W.	2.5.4.18.	2.4.18.5.	2.4.6.20.	2.4.6.20.	20.22.6.	20.22.23.	9.7.22.23.	9.7.	9.7.8.	7.8.9.	7.8.	8.11.	
60	E.	20.10.	20.22.10.	22.11.	11.	11.	2.12.11.	2.12.11.	2.12.	2 12.	2.	1.2.	1.2.4.7.	60
	W.	5.18.2.6.	2.4.5.6.18.	20.2.4.6.	20.2.4.6.22.	20.2.4.6.	20.4.	9.	9.	9.7.	7.9.11.	7.8.11.	8.11.	

1. α Tauri (Aldebaran).
3. α Orionis.
5. α Can. Min. (Procyon).
7. α Ursæ Majoris.
9. α Boötis (Arcturus).
11. α Aquilæ (Altair).
2. α Aurigæ (Capella).
4. α Geminorum (Castor).
6. α Leonis (Regulus).
8. γ Ursæ Majoris.
10. α Lyræ (Vega).
12. α Pegasi (Marcab.)

TABLE II.—*Continued.*

Latitude South. Degrees.		Sidereal Time. 0h.	1h.	2h.	3h.	4h.	5h.	6h.	7h.	8h.	9h.	10h	11h.	Latitude South. Degrees.
10	E.	1.14.	2.15.3.14.	2.15.16.	2.15.5.4.	17.4.	17.6.18.	17.0.	10.17.	10.17.20.	10.21.20.7.	9.21.8.22.	21.23.8.	10
	W.	11.24.	24.	24.	12.	12.	13.	13.2.	13.2.	2.1.	2.1.14.	15.17.3.14.	17.16.15.4.	
20	E.	15.14.1.	15.16.1.3.	16.15.3.2.	17.5.2.	17.18.4.2.	17.18.4.2.	19.0.	19.	19.21.20.	21.20.	21.9.22.	9.23.8.	20
	W.	11.	24.	24.12.	12.	12.		2.13.	2.13.	2.1.13.	1.	4.3.14.	15.16.4.	
30	E.	15.17.1.14.	17.15.16.1.	17.16.3.	17.5.	2.19.18.	19.18.4.2.	19.0.21.	21.	21.20.	21.22.20.	22.	9.23.	30
	W.	11.	24.	12.24.	12.24.	24.		2.	2.1.13.	4.1.13.	4.13.3.14.	4.3.14.	16.5.	
40	E.	17.15.14.	19.17.16.1.	19.16.3.1.	19.21.5.	19.21.5.	19.21.18.	21.0.4.	21.6.	20.6.	20.22.	23.22.24.	9.23.21.	40
	W.	21.11.	21.12.	21.12.	12.24.	24.	24.	1.24.	1.	4.1.13.	4.13.3.14.	13.3.11.6.	5.16.13.	
50	E.	14.	19.16.14.	19.16.3.	21.19.3.1.	21.19.5.	21.18.5.	21.18.5.	0.	20.0.	22.20.0.24.	24.23.22.	23.24.	50
	W.	19.21.12.	21.12.	21.12.	24.	24.	1.24.	1.24.	24.1.3.	3.	13.14.3.5.	13.5.14.	13.6.5.16.	
60	E.	14.	19.14.	19.14.	1.3.16.21.	1.3.5.18.21.	3.5.18.	5.18.	6.0.	6 20.	0.20.22.24.	0.20.22.23.24	20.22.23.24	60
	W.	19.21.12.	21.12.	21.			1.21.	3.1.21.	3.24.	5.3.14.	5.14.	5.14.	16.0.5.13.	

Latitude South. Degrees.		Sidereal Time. 1 h.	13h.	14h.	15h.	16h.	17h.	18h.	19h.	20h.	21h.	22h.	23h.	Latitude South. Degrees.
10	E.	8.23.	8.	10.	10.24.11.	10.24.	21.	12.	12.	13.	13.	13.		10
	W.	17.5.16.10.	17.7.	17.6.8.18.	19.17.8.	10.8.	19.21.8.	10.21.20.9.	21.9.22.	21.22.	10.23.	10.	10.24.	
20	E.	23.8.	8.	24.	24.10.	10.11.	10.	10.	13.12.	13.	13.			20
	W.	16.15.6.	15.17.	17.6.18.8.	17.8.	17.8.	10.9.	19.9.20.	10.10.21.22	21.10.22.	10.21.23.	10.23.	11.	
30	E.	9.	24.	24.	11.24.	8.11.	10.11.	10.13.	13.12.	13.12.		17.	16.17.	30
	W.	15.16.6.	15.0.	15.6.18.	17.	17.9.	17.9.	17.19.9.20.	19.17.10.22	19.17.10.21	21.10.19.23	21.23.	11.	
40	E.	9.24.	24.9.	9.24.	13.	13.11.	13.11.	13.10.	13.12.	12.	17.12.15.	17.16.	17.15.	40
	W.	16.6.6.	6.15.	15.6.18.	9.15.	9.17.	17.9.	17.20.	17.10.19.22	17.19.22.	19.21.23.	10.21.23.11.	19.21.11.	
50	E.	9.24.	9.	9.13.	13.	13.11.	11.13.	11.13.	11.15.	16.12.	16.12.17.	17.15.12.	17.15.	50
	W.	13.5.16.6.	6.15.18.	15.18.	9.15.	9.15.	15.20.	16.20.	17.22.	17.19.22.11	19.23.11.	19.21.22.11.	19.21.11.23	
60	E.		9.	9.12.	13.	13.	11.	11.	15.11.	16.	16.12.	12.15.	15.	60
	W.	16.13.6.8.	16.13.18.	18.	15.9.	20.15.	15.20.	15.20.22.	22.	11.22.	23.11.	23.11.	12.19.23.	

13. α Eridani (Achernar).
15. α Argus (Canopus).
17. β Argus.
19. α Crucis.
21. α Centauri.
23. α Scorpii (Antares).
14. β Orionis (Rigel).
16. α Canis Majoris (Sirius).
18. α Hydræ.
20. α Virginis (Spica).
22. α Libræ.
24. α Pavonis.

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TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

DECLINATION—*same Name as*—LATITUDE.

Apparent Time. A.M. h. m.	0° ° ′	1° ° ′	2° ° ′	3° ° ′	4° ° ′	5° ° ′	6° ° ′	7° ° ′	8° ° ′	9° ° ′	10° ° ′	11° ° ′	Apparent Time. P.M. h. m.
XII. 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	O. 0
XI. 56	178 47	178 46	178 45	178 44	178 44	178 43	178 42	178 41	178 40	178 39	178 38	178 36	4
52	177 34	177 33	177 31	177 29	177 28	177 26	177 24	177 22	177 20	177 18	177 16	177 13	8
48	176 22	176 20	176 17	176 14	176 12	176 9	176 6	176 3	176 0	175 57	175 54	175 50	12
44	175 10	175 7	175 3	174 59	174 56	174 52	174 48	174 44	174 40	174 36	174 32	174 27	16
40	173 58	173 54	173 50	173 45	173 41	173 36	173 31	173 26	173 21	173 16	173 10	173 4	20
36	172 46	172 41	172 36	172 31	172 26	172 20	172 14	172 8	172 2	171 55	171 48	171 41	24
32	171 34	171 28	171 22	171 16	171 10	171 4	170 57	170 49	170 42	170 35	170 27	170 18	28
28	170 22	170 15	170 8	170 1	169 55	169 48	169 40	169 31	169 23	169 15	169 6	168 56	32
24	169 10	169 3	168 55	168 47	168 40	168 32	168 23	168 13	168 4	167 55	167 45	167 34	36
20	167 59	167 51	167 42	167 33	167 25	167 16	167 6	166 55	166 45	166 35	166 24	166 12	40
16	166 48	166 39	166 29	166 19	166 10	166 0	165 49	165 38	165 27	165 16	165 4	164 51	44
12	165 37	165 27	165 17	165 6	164 56	164 45	164 33	164 21	164 9	163 57	163 44	163 30	48
8	164 26	164 15	164 4	163 53	163 42	163 30	163 17	163 4	162 51	162 38	162 24	162 10	52
4	163 15	163 4	162 52	162 40	162 28	162 15	162 1	161 47	161 33	161 19	161 5	160 50	56
XI. 0	162 5	161 53	161 40	161 27	161 14	161 0	160 46	160 31	160 16	160 1	159 46	159 30	I. 0
X. 56	160 55	160 42	160 29	160 15	160 1	159 46	159 31	159 16	159 0	158 44	158 28	158 11	4
52	159 45	159 31	159 17	159 3	158 48	158 33	158 17	158 1	157 44	157 27	157 10	156 52	8
48	158 36	158 21	158 6	157 51	157 36	157 20	157 3	156 46	156 29	156 11	155 53	155 34	12
44	157 27	157 11	156 56	156 40	156 24	156 7	155 49	155 31	155 13	154 55	154 36	154 16	16
40	156 18	156 1	155 45	155 29	155 12	154 54	154 36	154 17	153 58	153 39	153 19	152 58	20
36	155 9	154 52	154 35	154 18	154 0	153 42	153 23	153 3	152 44	152 24	152 3	151 41	24
32	154 1	153 43	153 26	153 8	152 49	152 30	152 10	151 50	151 30	151 9	150 47	150 25	28
28	152 53	152 35	152 17	151 58	151 39	151 19	150 58	150 37	150 16	149 55	149 32	149 10	32
24	151 46	151 27	151 8	150 49	150 29	150 8	149 47	149 25	149 3	148 41	148 18	147 55	36
20	150 39	150 19	150 0	149 40	149 19	148 58	148 36	148 14	147 51	147 28	147 5	146 41	40
16	149 32	149 12	148 52	148 31	148 10	147 48	147 26	147 3	146 40	146 16	145 52	145 27	44
12	148 25	148 5	147 44	147 23	147 1	146 39	146 16	145 53	145 29	145 4	144 39	144 13	48
8	147 19	146 59	146 37	146 15	145 53	145 30	145 7	144 43	144 18	143 53	143 27	143 0	52
4	146 13	145 53	145 31	145 8	144 45	144 22	143 58	143 33	143 8	142 42	142 15	141 48	56
X. 0	145 8	144 47	144 25	144 1	143 38	143 14	142 49	142 24	141 58	141 32	141 5	140 37	II. 0
IX. 56	144 4	143 42	143 19	142 55	142 31	142 7	141 41	141 16	140 49	140 23	139 55	139 26	4
52	143 0	142 37	142 13	141 49	141 25	141 0	140 34	140 8	139 41	139 14	138 45	138 16	8
48	141 56	141 32	141 8	140 44	140 19	139 53	139 27	139 0	138 33	138 5	137 36	137 7	12
44	140 53	140 28	140 4	139 39	139 13	138 47	138 20	137 53	137 25	136 57	136 28	135 58	16
40	139 50	139 24	139 0	138 34	138 8	137 42	137 14	136 47	136 18	135 50	135 20	134 50	20
36	138 47	138 21	137 56	137 30	137 4	136 37	136 9	135 41	135 12	134 43	134 13	133 43	24
32	137 44	137 18	136 53	136 26	136 0	135 33	135 5	134 36	134 7	133 37	133 7	132 36	28
28	136 42	136 16	135 50	135 23	134 56	134 29	134 0	133 31	133 2	132 32	132 1	131 30	32
24	135 40	135 14	134 47	134 20	133 53	133 25	132 56	132 27	131 57	131 27	130 56	130 24	36
20	134 39	134 13	133 45	133 18	132 50	132 22	131 53	131 23	130 53	130 23	129 51	129 19	40
16	133 38	133 12	132 44	132 16	131 48	131 19	130 50	130 20	129 49	129 19	128 47	128 14	44
12	132 38	132 11	131 43	131 15	130 46	130 17	129 47	129 17	128 46	128 15	127 43	127 10	48
8	131 38	131 11	130 43	130 14	129 45	129 15	128 45	128 15	127 44	127 12	126 40	126 7	52
4	130 39	130 11	129 43	129 14	128 44	128 14	127 44	127 13	126 42	126 10	125 37	125 4	56
IX. 0	129 40	129 11	128 43	128 14	127 44	127 13	126 43	126 12	125 40	125 8	124 35	124 2	III. 0

In North Latitude { *When Apparent Time is A.M. read the Azimuth from North to East.*
——— „ ——— *P.M.* ——— „ ——— *North to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

DECLINATION—*same Name as*—LATITUDE.

Apparent Time. A.M. h.	m.	12°	13°	14°	15°	16°	17°	18°	19°	20°	21°	22°	23°	Apparent Time. P.M. h.	m.
		° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′		
XII.	0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	O.	0
XI.	56	178 35	178 34	178 33	178 31	178 30	178 28	178 27	178 25	178 24	178 22	178 20	178 18		4
	52	177 10	177 8	177 6	177 3	177 0	176 57	176 54	176 51	176 48	176 44	176 41	176 37		8
	48	175 46	175 42	175 39	175 35	175 31	175 26	175 22	175 17	175 12	175 7	175 2	174 56		12
	44	174 22	174 17	174 12	174 7	174 1	173 55	173 49	173 43	173 37	173 30	173 23	173 15		16
	40	172 58	172 52	172 46	172 39	172 32	172 24	172 17	172 9	172 2	171 53	171 44	171 35		20
	36	171 34	171 27	171 19	171 11	171 3	170 54	170 45	170 36	170 27	170 16	170 6	169 55		24
	32	170 10	170 2	169 53	169 44	169 31	169 24	169 13	169 3	168 52	168 40	168 28	168 15		28
	28	168 47	168 37	168 27	168 17	168 6	167 54	167 42	167 30	167 17	167 4	166 50	166 35		32
	24	167 24	167 13	167 2	166 50	166 38	166 25	166 12	165 58	165 43	165 28	165 13	164 56		36
	20	166 1	165 49	165 37	165 24	165 10	164 56	164 42	164 27	164 10	163 53	163 37	163 18		40
	16	164 39	164 26	164 12	163 58	163 43	163 28	163 12	162 56	162 38	162 19	162 1	161 41		41
	12	163 17	163 3	162 48	162 33	162 17	162 0	161 43	161 25	161 6	160 46	160 25	160 5		48
	8	161 55	161 40	161 24	161 8	160 51	160 33	160 14	159 55	159 34	159 13	158 51	158 29		52
	4	160 34	160 18	160 1	159 43	159 25	159 6	158 46	158 26	158 4	157 41	157 18	156 54		56
XI.	0	159 13	158 56	158 38	158 19	157 59	157 39	157 18	156 57	156 34	156 10	155 45	155 19	I.	0
X.	56	157 53	157 35	157 16	156 56	156 35	156 14	155 52	155 29	155 5	154 40	154 13	153 46		4
	52	156 33	156 14	155 54	155 33	155 11	154 49	154 26	154 2	153 37	153 11	152 43	152 14		8
	48	155 14	154 54	154 33	154 11	153 48	153 25	153 1	152 36	152 10	151 42	151 13	150 43		12
	44	153 55	153 34	153 12	152 49	152 26	152 2	151 37	151 11	150 43	150 14	149 44	149 13		16
	40	152 37	152 15	151 52	151 28	151 4	150 39	150 13	149 46	149 17	148 47	148 16	147 44		20
	36	151 19	150 56	150 32	150 8	149 43	149 17	148 50	148 22	147 52	147 21	146 49	146 16		24
	32	150 2	149 38	149 14	148 49	148 23	147 56	147 28	146 59	146 28	145 56	145 23	144 49		28
	28	148 46	148 21	147 56	147 30	147 3	146 35	146 6	145 37	145 5	144 32	143 58	143 23		32
	24	147 30	147 5	146 39	146 12	145 44	145 15	144 45	144 15	143 42	143 9	142 34	141 58		36
	20	146 15	145 49	145 22	144 55	144 26	143 56	143 25	142 54	142 21	141 47	141 11	140 34		40
	16	145 0	144 34	144 6	143 38	143 8	142 38	142 6	141 34	141 0	140 26	139 49	139 11		44
	12	143 46	143 19	142 51	142 22	141 52	141 21	140 48	140 15	139 41	139 6	138 28	137 50		48
	8	142 33	142 5	141 36	141 7	140 36	140 5	139 31	138 57	138 22	137 47	137 9	136 30		52
	4	141 20	140 52	140 23	139 53	139 21	138 49	138 15	137 40	137 5	136 29	135 50	135 10		56
X.	0	140 8	139 40	139 10	138 39	138 7	137 34	136 59	136 24	135 48	135 11	134 31	133 51	II.	0
IX.	56	138 57	138 28	137 57	137 26	136 53	136 20	135 45	135 9	134 32	133 55	133 15	132 34		4
	52	137 47	137 17	136 46	136 14	135 41	135 7	134 31	133 55	133 18	132 40	131 59	131 18		8
	48	136 37	136 7	135 35	135 3	134 29	133 55	133 19	132 42	132 4	131 26	130 45	130 3		12
	44	135 28	134 57	134 25	133 52	133 18	132 44	132 7	131 30	130 52	130 13	129 32	128 49		16
	40	134 19	133 48	133 15	132 42	132 8	131 33	130 56	130 19	129 40	129 0	128 18	127 36		20
	36	133 11	132 40	132 6	131 33	130 58	130 23	129 46	129 8	128 28	127 48	127 6	126 24		24
	32	132 4	131 32	130 58	130 24	129 49	129 14	128 36	127 58	127 18	126 37	125 55	125 13		28
	28	130 57	130 25	129 51	129 16	128 41	128 5	127 27	126 49	126 8	125 27	124 45	124 3		32
	24	129 51	129 18	128 44	128 9	127 33	126 57	126 19	125 41	125 0	124 19	123 37	122 54		36
	20	128 46	128 12	127 38	127 3	126 27	125 50	125 12	124 33	123 52	123 11	122 29	121 46		40
	16	127 41	127 7	126 32	125 57	125 21	124 44	124 5	123 26	122 45	122 4	121 21	120 38		44
	12	126 36	126 2	125 27	124 52	124 15	123 38	122 59	122 20	121 39	120 58	120 15	119 31		48
	8	125 33	124 58	124 23	123 48	123 11	122 33	121 54	121 15	120 34	119 52	119 9	118 25		52
	4	124 30	123 55	123 20	122 44	122 7	121 29	120 50	120 11	119 29	118 47	118 4	117 20		56
IX.	0	123 28	122 53	122 17	121 41	121 3	120 25	119 46	119 7	118 25	117 43	117 0	116 16	III.	0

In South Latitude { *When Apparent Time is A.M. read the Azimuth from South to East.*
{ ——— „ ——— *P.M.* ——— „ ——— *South to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

Apparent Time. A.M.	DECLINATION—*same Name as*—LATITUDE.											
	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	1
h. m.	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	°
IX. 0	129 40	129 11	128 43	128 14	127 44	127 13	126 43	126 12	125 40	125 8	124 35	12
VIII. 56	128 41	128 12	127 43	127 14	126 44	126 13	125 42	125 11	124 39	124 7	123 34	12
52	127 42	127 13	126 44	126 15	125 45	125 14	124 43	124 11	123 39	123 6	122 33	12
48	126 44	126 15	125 46	125 16	124 46	124 15	123 43	123 11	122 39	122 6	121 33	120
44	125 46	125 17	124 48	124 18	123 47	123 16	122 44	122 12	121 39	121 6	120 33	119
40	124 49	124 20	123 50	123 20	122 49	122 17	121 45	121 13	120 40	120 7	119 33	118
36	123 52	123 23	122 53	122 22	121 51	121 19	120 47	120 14	119 41	119 8	118 34	118
32	122 55	122 26	121 56	121 25	120 53	120 21	119 49	119 16	118 43	118 10	117 36	117
28	121 59	121 30	120 59	120 28	119 56	119 24	118 51	118 18	117 46	117 12	116 38	116
24	121 3	120 34	120 3	119 31	118 59	118 27	117 54	117 21	116 48	116 14	115 40	115
20	120 7	119 38	119 7	118 35	118 3	117 30	116 57	116 24	115 51	115 17	114 43	114
16	119 12	118 43	118 11	117 39	117 7	116 31	116 1	115 28	114 54	114 20	113 46	113
12	118 17	117 48	117 16	116 43	116 11	115 38	115 5	114 32	113 58	113 24	112 49	112
8	117 22	116 53	116 21	115 48	115 16	114 43	114 10	113 37	113 3	112 28	111 53	111
4	116 28	115 58	115 26	114 53	114 21	113 48	113 15	112 42	112 8	111 33	110 58	110
VIII. 0	115 35	115 4	114 32	113 59	113 26	112 53	112 20	111 47	111 13	110 38	110 3	109
VII. 56	114 41	114 10	113 38	113 5	112 32	111 59	111 26	110 52	110 18	109 43	109 8	108
52	113 47	113 16	112 44	112 11	111 38	111 5	110 32	109 58	109 23	108 48	108 13	107
48	112 54	112 22	111 50	111 17	110 44	110 11	109 38	109 4	108 29	107 54	107 19	106
44	112 1	111 29	110 56	110 23	109 50	109 17	108 44	108 10	107 35	107 0	106 25	105
40	111 8	110 36	110 3	109 30	108 57	108 23	107 50	107 16	106 41	106 6	105 31	104
36	110 16	109 43	109 10	108 37	108 4	107 30	106 57	106 23	105 48	105 13	104 38	104
32	109 24	108 51	108 18	107 44	107 11	106 37	106 4	105 30	104 55	104 20	103 45	103
28	108 32	107 59	107 26	106 52	106 19	105 45	105 11	104 37	104 2	103 27	102 52	102
24	107 40	107 7	106 34	106 0	105 27	104 53	104 19	103 45	103 10	102 35	102 0	101
20	106 48	106 15	105 42	105 8	104 35	104 1	103 27	102 53	102 18	101 43	101 8	100
16	105 56	105 23	104 50	104 16	103 43	103 9	102 35	102 1	101 26	100 51	100 16	99
12	105 4	104 31	103 58	103 25	102 51	102 17	101 43	101 9	100 35	100 0	99 25	98
8	104 13	103 40	103 7	102 34	102 0	101 26	100 52	100 17	99 43	99 9	98 33	97
4	103 22	102 49	102 16	101 43	101 9	100 35	100 1	99 26	98 52	98 18	97 42	97
VII. 0	102 31	101 58	101 25	100 52	100 18	99 44	99 10	98 35	98 1	97 27	96 51	96
VI. 56	101 40	101 7	100 34	100 1	99 27	98 53	98 19	97 44	97 10	96 36	96 0	95
52	100 49	100 16	99 43	99 10	98 36	98 2	97 28	96 53	96 19	95 45	95 9	94
48	99 59	99 26	98 53	98 19	97 45	97 11	96 37	96 3	95 29	94 54	94 19	93
44	99 9	98 35	98 2	97 28	96 55	96 21	95 47	95 13	94 38	94 3	93 28	92
40	98 19	97 45	97 12	96 38	96 5	95 31	94 57	94 23	93 48	93 13	92 38	92
36	97 29	96 55	96 22	95 48	95 15	94 41	94 7	93 33	92 58	92 23	91 48	91
32	96 39	96 5	95 32	94 58	94 25	93 51	93 17	92 43	92 8	91 33	90 58	90
28	95 49	95 15	94 42	94 8	93 35	93 1	92 27	91 53	91 18	90 43	90 8	89
24	94 59	94 25	93 52	93 18	92 45	92 11	91 37	91 3	90 28	89 53	89 18	88
20	94 9	93 35	93 2	92 28	91 55	91 21	90 47	90 13	89 38	89 3	88 28	87
16	93 19	92 45	92 12	91 38	91 5	90 31	89 57	89 23	88 48	88 13	87 39	87
12	92 29	91 55	91 22	90 48	90 15	89 41	89 7	88 33	87 59	87 24	86 50	86
8	91 39	91 5	90 32	89 58	89 25	88 51	88 17	87 43	87 9	86 34	86 0	85
4	90 49	90 15	89 42	89 9	88 35	88 1	87 27	86 53	86 19	85 45	85 11	84
VI. 0	90 0	89 26	88 53	88 20	87 46	87 12	86 38	86 3	85 30	84 56	84 22	83

In North Latitude { *When Apparent Time is A.M. read the Azimuth from Nor*
——— " ——— *P.M.* ——— " ——— *Nor*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

Apparent Time. A.M.	DECLINATION—*same Name as*—LATITUDE.												Apparent Time. P.M.
	12°	13°	14°	15°	16°	17°	18°	19°	20°	21°	22°	23°	
h. m.	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	h. m.
IX. 0	123 28	122 53	122 17	121 41	121 3	120 25	119 46	119 7	118 25	117 43	117 0	116 16	*III.* 0
VIII. 56	122 26	121 51	121 15	120 39	120 1	119 23	118 44	118 4	117 22	116 40	115 57	115 13	4
52	121 25	120 50	120 14	119 37	118 59	118 21	117 42	117 2	116 20	115 38	114 54	114 10	8
48	120 24	119 49	119 13	118 35	117 57	117 19	116 40	116 0	115 18	114 36	113 52	113 8	12
44	119 24	118 49	118 12	117 34	116 56	116 18	115 39	114 59	114 17	113 35	112 51	112 6	16
40	118 24	117 49	117 12	116 34	115 56	115 18	114 39	113 59	113 17	112 34	111 50	111 5	20
36	117 25	116 49	116 12	115 34	114 56	114 18	113 39	112 59	112 17	111 34	110 50	110 5	24
32	116 26	115 50	115 13	114 35	113 57	113 19	112 40	112 0	111 18	110 35	109 51	109 6	28
28	115 27	114 51	114 14	113 36	112 58	112 20	111 41	111 1	110 19	109 36	108 52	108 7	32
24	114 29	113 53	113 16	112 38	112 0	111 22	110 42	110 2	109 20	108 38	107 54	107 9	36
20	113 32	112 56	112 19	111 41	111 3	110 24	109 44	109 4	108 22	107 40	106 56	106 12	40
16	112 35	111 59	111 22	110 44	110 6	109 27	108 47	108 7	107 25	106 43	105 59	105 15	44
12	111 38	111 2	110 25	109 47	109 9	108 30	107 50	107 10	106 28	105 46	105 3	104 19	48
8	110 42	110 6	109 29	108 51	108 13	107 34	106 54	106 14	105 32	104 50	104 7	103 24	52
4	109 46	109 10	108 33	107 55	107 17	106 38	105 58	105 18	104 36	103 54	103 12	102 29	56
VIII. 0	108 51	108 14	107 37	106 59	106 21	105 42	105 3	104 23	103 41	102 59	102 17	101 34	*IV.* 0
VII. 56	107 56	107 19	106 42	106 4	105 26	104 47	104 8	103 29	102 47	102 5	101 23	100 40	4
52	107 2	106 25	105 48	105 10	104 32	103 53	103 14	102 35	101 53	101 11	100 29	99 46	8
48	106 8	105 31	104 54	104 16	103 38	102 59	102 20	101 41	100 59	100 17	99 35	98 52	12
44	105 14	104 37	104 0	103 22	102 44	102 5	101 26	100 47	100 6	99 24	98 42	97 59	16
40	104 20	103 43	103 6	102 28	101 50	101 12	100 33	99 54	99 13	98 31	97 49	97 6	20
36	103 27	102 50	102 13	101 35	100 57	100 19	99 40	99 1	98 20	97 38	96 56	96 14	24
32	102 34	101 57	101 20	100 42	100 4	99 26	98 47	98 8	97 27	96 46	96 4	95 22	28
28	101 41	101 4	100 27	99 50	99 12	98 33	97 55	97 16	96 35	95 54	95 12	94 30	32
24	100 49	100 12	99 35	98 58	98 20	97 41	97 3	96 24	95 43	95 2	94 21	93 39	36
20	99 57	99 20	98 43	98 6	97 28	96 49	96 11	95 32	94 52	94 11	93 30	92 48	40
16	99 5	98 28	97 51	97 14	96 36	95 58	95 20	94 41	94 1	93 20	92 39	91 58	41
12	98 13	97 37	97 0	96 23	95 45	95 7	94 29	93 50	93 10	92 29	91 49	91 8	48
8	97 22	96 46	96 0	95 32	94 54	94 16	93 38	92 59	92 19	91 39	90 59	90 18	52
4	96 31	95 55	95 18	94 41	94 3	93 25	92 47	92 9	91 29	90 49	90 9	89 28	56
VII. 0	95 40	95 4	94 27	93 50	93 13	92 35	91 57	91 19	90 40	90 0	89 20	88 39	*V.* 0
VI. 56	94 49	94 13	93 36	92 59	92 22	91 45	91 7	90 29	89 50	89 10	88 30	87 50	4
52	93 58	93 22	92 46	92 9	91 32	90 55	90 17	89 39	89 0	88 20	87 41	87 1	8
48	93 8	92 32	91 56	91 19	90 42	90 5	89 28	88 50	88 11	87 31	86 52	86 12	12
44	92 18	91 42	91 6	90 29	89 52	89 15	88 38	88 0	87 21	86 42	86 3	85 23	16
40	91 28	90 52	90 16	89 39	89 3	88 26	87 49	87 11	86 32	85 53	85 14	84 35	20
36	90 38	90 2	89 26	88 50	88 14	87 37	87 0	86 22	85 44	85 5	84 26	83 47	24
32	89 48	89 12	88 36	88 0	87 24	86 48	86 11	85 33	84 55	84 16	83 38	82 59	28
28	88 58	88 22	87 47	87 11	86 35	85 59	85 22	84 44	84 6	83 28	82 50	82 11	32
24	88 8	87 33	86 58	86 22	85 46	85 10	84 33	83 56	83 18	82 40	82 2	81 23	36
20	87 18	86 43	86 8	85 33	84 57	84 21	83 44	83 7	82 30	81 52	81 14	80 35	40
16	86 29	85 51	85 19	84 44	84 8	83 32	82 56	82 19	81 42	81 4	80 26	79 47	44
12	85 40	85 5	84 30	83 55	83 19	82 43	82 7	81 31	80 51	80 16	79 38	79 0	48
8	84 51	84 16	83 41	83 6	82 30	81 54	81 19	80 43	80 6	79 28	78 51	78 13	52
4	84 2	83 27	82 52	82 17	81 42	81 6	80 31	79 55	79 18	78 40	78 3	77 26	56
VI. 0	83 13	82 38	82 3	81 28	80 53	80 18	79 43	79 7	78 30	77 53	77 16	76 39	*VI.* 0

In South Latitude { *When Apparent Time is A.M. read the Azimuth from South to East.*
{ ——— " ——— *P.M.* ——— " ——— *South to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

Apparent Time A.M. h.	m.	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	Apparent Time P.M. h.	m.
		DECLINATION—*contrary Name to*—LATITUDE.													
		° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′		
XII.	0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	O.	0
XI.	56	178 47	178 48	178 49	178 50	178 50	178 51	178 52	178 53	178 53	178 54	178 55	178 56		4
	52	177 34	177 36	177 38	177 40	177 41	177 43	177 44	177 46	177 47	177 48	177 50	177 52		8
	48	176 22	176 25	176 27	176 30	176 32	176 35	176 37	176 39	176 41	176 43	176 45	176 48		12
	44	175 10	175 13	175 16	175 20	175 23	175 26	175 29	175 32	175 35	175 38	175 41	175 44		16
	40	173 58	174 2	174 6	174 10	174 14	174 18	174 21	174 25	174 29	174 33	174 36	174 40		20
	36	172 46	172 51	172 56	173 1	173 5	173 10	173 14	173 18	173 23	173 28	173 32	173 36		24
	32	171 34	171 40	171 45	171 51	171 56	172 2	172 7	172 12	172 17	172 23	172 27	172 32		28
	28	170 22	170 29	170 35	170 42	170 48	170 54	171 0	171 6	171 12	171 18	171 23	171 29		32
	24	169 10	169 18	169 25	169 33	169 40	169 47	169 53	170 0	170 6	170 13	170 19	170 26		36
	20	167 59	168 7	168 15	168 24	168 31	168 39	168 46	168 54	169 1	169 8	169 15	169 22		40
	16	166 48	166 57	167 6	167 15	167 23	167 32	167 40	167 48	167 55	168 3	168 11	168 19		44
	12	165 37	165 47	165 56	166 6	166 15	166 25	166 33	166 42	166 50	166 59	167 7	167 16		48
	8	164 26	164 37	164 47	164 57	165 7	165 18	165 27	165 36	165 45	165 55	166 4	166 13		52
	4	163 15	163 27	163 38	163 49	164 0	164 11	164 20	164 30	164 40	164 51	165 0	165 10		56
XI.	0	162 5	162 18	162 29	162 41	162 52	163 4	163 14	163 25	163 36	163 47	163 57	164 7	I.	0
X.	56	160 55	161 8	161 20	161 33	161 45	161 57	162 8	162 20	162 31	162 43	162 53	163 4		4
	52	159 45	159 59	160 12	160 25	160 38	160 51	161 3	161 15	161 27	161 39	161 50	162 2		8
	48	158 36	158 50	159 3	159 17	159 31	159 45	159 57	160 10	160 23	160 36	160 48	161 0		12
	44	157 27	157 41	157 55	158 10	158 24	158 39	158 52	159 6	159 19	159 32	159 45	159 58		16
	40	156 18	156 33	156 48	157 3	157 18	157 33	157 47	158 2	158 15	158 29	158 42	158 56		20
	36	155 9	155 25	155 41	155 57	156 12	156 28	156 43	156 58	157 12	157 26	157 40	157 54		24
	32	154 1	154 18	154 34	154 51	155 7	155 23	155 38	155 54	156 8	156 23	156 38	156 53		28
	28	152 53	153 11	153 28	153 45	154 2	154 18	154 34	154 50	155 5	155 21	155 36	155 52		32
	24	151 46	152 4	152 22	152 40	152 57	153 14	153 30	153 47	154 3	154 19	154 35	154 51		36
	20	150 39	150 58	151 16	151 35	151 52	152 10	152 27	152 44	153 0	153 17	153 33	153 50		40
	16	149 32	149 52	150 11	150 30	150 48	151 6	151 33	151 41	151 58	152 15	152 32	152 49		44
	12	148 25	148 46	149 5	149 25	149 44	150 2	150 20	150 39	150 56	151 14	151 31	151 49		48
	8	147 19	147 40	148 0	148 21	148 40	148 59	149 18	149 37	149 55	150 13	150 31	150 49		52
	4	146 13	146 35	146 55	147 17	147 36	147 56	148 15	148 35	148 53	149 12	149 30	149 49		56
X.	0	145 8	145 30	145 51	146 13	146 33	146 53	147 13	147 33	147 52	148 12	148 30	148 49	II.	0
IX.	56	144 4	144 26	144 47	145 10	145 30	145 51	146 11	146 32	146 52	147 12	147 31	147 50		4
	52	143 0	143 22	143 44	144 7	144 28	144 49	145 10	145 31	145 51	146 12	146 32	146 51		8
	48	141 56	142 19	142 41	143 4	143 26	143 48	144 9	144 31	144 52	145 13	145 33	145 53		12
	44	140 53	141 16	141 39	142 2	142 24	142 47	143 9	143 31	143 52	144 14	144 31	144 55		16
	40	139 50	140 13	140 37	141 0	141 23	141 46	142 9	142 31	142 53	143 15	143 36	143 57		20
	36	138 47	139 11	139 35	139 59	140 22	140 46	141 9	141 31	141 53	142 16	142 37	142 59		24
	32	137 44	138 9	138 33	138 58	139 22	139 46	140 9	140 32	140 54	141 17	141 39	142 1		28
	28	136 42	137 8	137 32	137 57	138 21	138 46	139 9	139 33	139 56	140 19	140 41	141 4		32
	24	135 40	136 7	136 32	136 57	137 21	137 46	138 10	138 34	138 57	139 21	139 44	140 7		36
	20	134 39	135 6	135 31	135 57	136 21	136 46	137 11	137 36	137 59	138 23	138 46	139 10		40
	16	133 38	134 6	134 31	134 57	135 22	135 47	136 12	136 38	137 2	137 26	137 49	138 13		44
	12	132 38	133 6	133 32	133 58	134 23	134 48	135 14	135 40	136 4	136 29	136 53	137 17		48
	8	131 38	132 6	132 32	132 59	133 24	133 50	134 16	134 43	135 7	135 32	135 56	136 21		52
	4	130 39	131 6	131 33	132 1	132 26	132 52	133 19	133 46	134 10	134 35	135 0	135 25		56
IX.	0	129 40	130 7	130 35	131 3	131 29	131 55	132 22	132 49	133 14	133 39	134 4	134 30	III.	0

In North Latitude { *When Apparent Time is A.M. read the Azimuth from North to East.*
{ ——— „ ——— *P.M.* ——— „ ——— *North to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

DECLINATION—*contrary Name to*—LATITUDE.

Apparent Time. A.M. h.	m.	12° ° ′	13° ° ′	14° ° ′	15° ° ′	16° ° ′	17° ° ′	18° ° ′	19° ° ′	20° ° ′	21° ° ′	22° ° ′	23° ° ′	Apparent Time. P.M. h.	m.
XII.	0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	180 0	*O.*	0
XI.	56	178 56	178 57	178 57	178 58	178 59	179 0	179 0	179 1	179 1	179 2	179 2	179 3		4
	52	177 53	177 54	177 55	177 57	177 58	178 0	178 1	178 2	178 3	178 4	178 5	178 6		8
	48	176 50	176 52	176 54	176 56	176 58	177 0	177 1	177 3	177 5	177 7	177 8	177 10		12
	44	175 46	175 49	175 52	175 54	175 57	176 0	176 2	176 4	176 6	176 9	176 11	176 14		16
	40	174 43	174 47	174 50	174 53	174 56	175 0	175 3	175 6	175 9	175 12	175 15	175 18		20
	36	173 40	173 45	173 48	173 52	173 56	174 0	174 4	174 8	174 11	174 15	174 18	174 22		24
	32	172 37	172 42	172 46	172 51	172 55	173 0	173 4	173 9	173 13	173 17	173 21	173 26		28
	28	171 34	171 40	171 45	171 50	171 55	172 0	172 5	172 11	172 15	172 20	172 25	172 30		32
	24	170 32	170 38	170 44	170 50	170 55	171 1	171 7	171 13	171 18	171 23	171 28	171 34		36
	20	169 29	169 36	169 42	169 49	169 55	170 1	170 7	170 14	170 20	170 26	170 32	170 38		40
	16	168 26	168 34	168 41	168 48	168 54	169 1	169 8	169 16	169 22	169 29	169 35	169 42		44
	12	167 24	167 32	167 40	167 48	167 55	168 2	168 10	168 18	168 25	168 32	168 39	168 46		48
	8	166 21	166 30	166 38	166 47	166 55	167 3	167 11	167 20	167 27	167 35	167 42	167 50		52
	4	165 19	165 28	165 37	165 47	165 55	166 4	166 13	166 22	166 30	166 38	166 46	166 55		56
XI.	0	164 17	164 27	164 37	164 47	164 56	165 5	165 14	165 24	165 33	165 42	165 50	166 0	*I.*	0
X.	56	163 15	163 25	163 35	163 46	163 56	164 6	164 16	164 26	164 35	164 45	164 54	165 4		4
	52	162 13	162 24	162 35	162 46	162 56	163 7	163 17	163 28	163 38	163 49	163 59	164 9		8
	48	161 11	161 23	161 34	161 46	161 57	162 8	162 19	162 30	162 41	162 53	163 3	163 14		12
	44	160 10	160 22	160 34	160 46	160 58	161 10	161 21	161 33	161 45	161 57	162 8	162 19		16
	40	159 8	159 21	159 34	159 46	159 59	160 12	160 24	160 36	160 48	161 1	161 12	161 24		20
	36	158 7	158 21	158 34	158 47	159 0	159 14	159 26	159 39	159 52	160 5	160 17	160 29		24
	32	157 7	157 21	157 34	157 48	158 2	158 16	158 29	158 42	158 55	159 9	159 21	159 34		28
	28	156 6	156 21	156 35	156 49	157 3	157 18	157 32	157 45	157 59	158 13	158 26	158 40		32
	24	155 6	155 21	155 35	155 50	156 5	156 21	156 35	156 49	157 3	157 17	157 31	157 46		36
	20	154 5	154 21	154 36	154 52	155 7	155 23	155 38	155 53	156 7	150 22	156 36	156 51		40
	16	153 5	153 21	153 37	153 54	154 10	154 26	154 41	154 57	155 12	155 27	155 42	155 57		44
	12	152 5	152 22	152 39	152 56	153 12	153 29	153 45	154 1	154 16	154 32	154 47	155 3		48
	8	151 6	151 23	151 40	151 58	152 15	152 32	152 48	153 5	153 21	153 37	153 53	154 9		52
	4	150 6	150 24	150 42	151 1	151 18	151 35	151 52	152 9	152 26	152 42	152 59	153 15		56
X.	0	149 7	149 26	149 45	150 4	150 21	150 38	150 56	151 14	151 31	151 48	152 5	152 22	*II.*	0
IX.	56	148 9	148 28	148 47	149 6	149 24	149 42	150 0	150 18	150 36	150 53	151 11	151 29		4
	52	147 11	147 30	147 49	148 9	148 27	148 46	149 4	149 23	149 41	149 59	150 17	150 36		8
	48	146 13	146 33	146 52	147 12	147 31	147 50	148 9	148 28	148 46	149 5	149 24	149 43		12
	44	145 15	145 36	145 55	146 15	146 35	146 54	147 14	147 33	147 52	148 11	148 30	148 50		16
	40	144 18	144 39	144 59	145 19	145 39	145 59	146 19	146 39	146 58	147 18	147 37	147 57		20
	36	143 20	143 42	144 2	144 23	144 43	145 4	145 24	145 45	146 5	146 25	146 45	147 5		24
	32	142 23	142 45	143 6	143 27	143 48	144 9	144 30	144 51	145 11	145 32	145 52	146 13		28
	28	141 26	141 49	142 10	142 31	142 53	143 14	143 35	143 57	144 18	144 39	145 0	145 21		32
	24	140 30	140 53	141 14	141 36	141 58	142 20	142 41	143 3	143 24	143 46	144 7	144 29		36
	20	139 33	139 57	140 19	140 41	141 3	141 26	141 47	142 9	142 31	142 53	143 15	143 37		40
	16	138 37	139 1	139 23	139 46	140 9	140 32	140 54	141 16	141 38	142 1	142 23	142 45		44
	12	137 41	138 5	138 28	138 51	139 14	139 38	140 0	140 23	140 46	141 9	141 31	141 54		48
	8	136 45	137 10	137 33	137 57	138 20	138 44	139 7	139 30	139 53	140 17	140 40	141 3		52
	4	135 50	136 15	136 39	137 3	137 26	137 50	138 14	138 38	139 1	139 25	139 48	140 12		56
IX.	0	134 55	135 20	135 44	136 9	136 33	136 57	137 21	137 46	138 9	138 33	138 57	139 21	*III.*	0

In South Latitude { *When Apparent Time is A.M. read the Azimuth from South to East.*
{ ——— " ——— *P.M.* ——— " ——— *South to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

Apparent Time. A.M.	DECLINATION—*contrary Name to*—LATITUDE. 0°	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°	11°	Apparent Time. P.M.
h. m.	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	h. m.
IX. 0	129 40	130 7	130 35	131 3	131 29	131 55	132 22	132 49	133 14	133 39	134 4	134 30	*III.* 0
VIII. 56	128 41	129 9	129 37	130 5	130 31	130 58	131 25	131 52	132 17	132 43	133 9	133 35	4
52	127 42	128 11	128 39	129 7	129 34	130 1	130 28	130 55	131 21	131 47	132 13	132 40	8
48	126 44	127 13	127 41	128 10	128 37	129 4	129 31	129 59	130 25	130 52	131 18	131 45	12
44	125 46	126 16	126 44	127 13	127 40	128 8	128 35	129 3	129 30	129 57	130 24	130 51	16
40	124 49	125 19	125 48	126 17	126 44	127 12	127 40	128 8	128 35	129 2	129 29	129 57	20
36	123 52	124 22	124 51	125 21	125 49	126 17	126 45	127 13	127 40	128 8	128 35	129 3	24
32	122 55	123 26	123 55	124 25	124 53	125 22	125 50	126 18	126 46	127 14	127 41	128 9	28
28	121 59	122 30	122 59	123 29	123 58	124 27	124 55	125 24	125 52	136 20	126 48	127 16	32
24	121 3	121 34	122 4	122 34	123 3	123 32	124 1	124 30	124 58	125 26	125 54	126 23	36
20	120 7	120 39	121 9	121 39	122 8	122 37	123 6	123 36	124 4	124 33	125 1	125 30	40
16	119 12	119 44	120 14	120 44	121 13	121 43	122 12	122 42	123 11	123 40	124 8	124 37	44
12	118 17	118 49	119 19	119 50	120 19	120 49	121 19	121 49	122 18	122 47	123 16	123 45	48
8	117 22	117 55	118 25	118 56	119 25	119 55	120 25	120 56	121 25	121 54	122 23	122 53	52
4	116 28	117 1	117 31	118 2	118 32	119 2	119 32	120 3	120 32	121 1	121 31	122 1	56
VIII. 0	115 35	116 7	116 37	117 8	117 38	118 9	118 39	119 10	119 39	120 9	120 39	121 9	*IV.* 0
VII. 56	114 41	115 13	115 44	116 15	116 45	117 16	117 46	118 17	118 47	119 17	119 47	120 17	4
52	113 47	114 19	114 50	115 22	115 52	116 23	116 54	117 25	117 55	118 25	118 55	119 25	8
48	112 54	113 26	113 57	114 29	115 0	115 31	116 2	116 33	117 3	117 33	118 3	118 34	12
44	112 1	112 33	113 4	113 36	114 7	114 38	115 9	115 41	116 11	116 42	117 12	117 43	16
40	111 8	111 40	112 12	112 44	113 15	113 46	114 17	114 49	115 20	115 51	116 21	116 52	20
36	110 16	110 48	111 20	111 52	112 23	112 54	113 25	113 57	114 28	115 0	115 30	116 1	24
32	109 21	109 56	110 28	111 0	111 31	112 2	112 33	113 5	113 37	114 9	114 39	115 10	28
28	108 32	109 4	109 36	110 8	110 39	111 11	111 42	112 14	112 46	113 18	113 49	114 20	32
24	107 40	108 12	108 44	109 16	109 48	110 20	110 51	111 23	111 55	112 27	112 58	113 30	36
20	106 48	107 20	107 52	108 24	108 56	109 29	110 0	110 32	111 4	111 36	112 8	112 40	40
16	105 56	106 29	107 1	107 33	108 5	108 38	109 9	109 41	110 13	110 45	111 17	111 50	44
12	105 4	105 38	106 10	106 42	107 14	107 47	108 18	108 50	109 22	109 55	110 27	111 0	48
8	104 13	104 47	105 19	105 51	106 23	106 56	107 28	108 0	108 32	109 5	109 37	110 10	52
4	103 22	103 56	104 28	105 0	105 32	106 5	106 37	107 10	107 42	108 15	108 47	109 20	56
VII. 0	102 31	103 5	103 37	104 10	104 42	105 15	105 47	106 20	106 52	107 25	107 58	108 30	*V.* 0
VI. 56	101 40	102 14	102 46	103 19	103 52	104 25	101 57	105 30	106 2	106 35	107 9	107 41	4
52	100 49	101 23	101 56	102 29	103 2	103 35	104 7	104 40	105 12	105 46	106 19	106 52	8
48	99 59	100 33	101 6	101 39	102 12	102 45	103 17	103 50	104 25	104 56	105 29	106 2	12
44	99 9	99 42	100 15	100 49	101 22	101 55	102 27	103 0	103 34	104 7	104 40	105 13	16
40	98 19	98 52	99 25	99 59	100 32	101 5	101 37	102 11	102 44	103 18	103 51	104 24	20
36	97 29	98 2	98 35	99 9	99 42	100 15	100 48	101 22	101 55	102 28	103 1	103 34	24
32	96 39	97 12	97 45	98 19	98 52	99 25	99 59	100 33	101 6	101 39	102 12	102 45	28
28	95 49	96 22	96 55	97 29	98 2	98 36	99 9	99 43	100 16	100 49	101 32	101 56	32
24	94 59	95 32	96 5	96 39	97 10	97 46	98 19	98 53	99 26	99 59	100 33	101 7	36
20	94 9	94 42	95 15	95 49	96 22	96 56	97 29	98 3	98 36	99 10	99 44	100 18	40
16	93 19	93 52	94 25	94 59	95 32	96 6	96 40	97 14	97 47	98 21	98 55	99 29	44
12	92 29	93 2	93 35	94 10	94 43	95 17	95 51	96 25	96 58	97 31	98 5	98 40	48
8	91 39	92 12	92 46	93 20	93 53	94 27	95 1	95 35	96 8	96 42	97 16	97 51	52
4	90 49	91 23	91 56	92 30	93 3	93 37	94 11	94 46	95 19	95 53	96 27	97 1	56
VI. 0	90 0	90 34	91 7	91 40	92 14	92 48	93 22	93 57	94 30	95 4	95 38	96 12	*VI.* 0

In North Latitude { *When Apparent Time is A.M. read the Azimuth from North to East.*
—— " —— *P.M.* —— " —— *North to West.*

TABLE III.—SUN'S TRUE BEARING OR AZIMUTH.

LATITUDE 56°.

Apparent Time. A.M.	DECLINATION—*contrary Name to*—LATITUDE.												Apparent Time. P.M.
	12°	13°	14°	15°	16°	17°	18°	19°	20°	21°	22°	23°	
h. m.	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	h. m.
IX. 0	134 55	135 20	135 44	136 9	136 33	136 57	137 21	137 46	138 9	138 33	138 57	139 21	III. 0
VIII. 56	134 0	134 25	134 50	135 15	135 39	136 4	136 28	136 53	137 17	137 41	138 5	138 30	4
52	133 5	133 31	133 56	134 21	134 46	135 11	135 36	136 1	136 25	136 50	137 14	137 40	8
48	132 11	132 37	133 2	133 28	133 53	134 19	134 44	135 9	135 34	135 59	136 24	136 50	12
44	131 17	131 43	132 9	132 35	133 1	133 27	133 52	134 17	134 43	135 8	135 34	136 0	16
40	130 23	130 49	131 15	131 42	132 8	132 35	133 0	133 26	133 52	134 18	134 44	135 10	20
36	129 29	129 56	130 22	130 49	131 16	131 43	132 9	132 35	133 1	133 28	133 54	134 20	24
32	128 36	129 3	129 30	129 57	130 24	130 51	131 17	131 44	132 11	132 38	133 4	133 30	28
28	127 43	128 10	128 37	129 5	129 32	129 59	130 26	130 53	131 20	131 47	132 12	132 40	32
24	126 50	127 18	127 45	128 13	128 40	129 8	129 35	130 2	130 29	130 57	131 23	131 51	36
20	125 58	126 26	126 53	127 21	127 49	128 17	128 44	129 11	129 39	130 7	130 34	131 2	40
16	125 5	125 34	126 1	126 29	126 57	127 26	127 53	128 20	128 48	129 18	129 45	130 13	44
12	124 13	124 42	125 10	125 38	126 6	126 35	127 2	127 30	127 58	128 28	128 56	129 24	48
8	123 21	123 50	124 18	124 47	125 15	125 44	126 12	126 40	127 8	127 38	128 6	128 35	52
4	122 29	122 58	123 27	123 56	124 25	124 54	125 22	125 51	126 19	126 48	127 17	127 46	56
VIII. 0	121 38	122 7	122 35	123 5	123 34	124 4	124 32	125 1	125 30	125 59	126 28	126 58	IV. 0
VII. 56	120 46	121 16	121 44	122 14	122 43	123 13	123 42	124 12	124 41	125 10	125 40	126 10	4
52	119 55	120 25	120 54	121 24	121 53	122 23	122 51	123 22	123 52	124 21	124 51	125 21	8
48	119 4	119 34	120 4	120 34	121 3	121 32	122 2	122 33	123 3	123 33	124 3	124 33	12
44	118 13	118 43	119 13	119 44	120 13	120 43	121 13	121 44	122 14	122 44	123 14	123 45	16
40	117 22	117 52	118 23	118 54	119 24	119 54	120 24	120 55	121 25	121 56	122 26	122 57	20
36	116 31	117 2	117 33	118 4	118 35	119 5	119 35	120 6	120 37	121 8	121 39	122 10	24
32	115 41	116 12	116 43	117 24	117 45	118 16	118 46	119 17	119 48	120 19	120 51	121 22	28
28	114 51	115 22	115 53	116 25	116 56	117 27	117 58	118 29	119 0	119 31	120 3	120 35	32
24	114 1	114 32	115 4	115 35	116 6	116 38	117 9	117 40	118 11	118 43	119 15	119 47	36
20	113 11	113 43	114 15	114 46	115 17	115 49	116 20	116 51	117 23	117 55	118 27	119 0	40
16	112 21	112 53	113 25	113 57	114 28	115 0	115 31	116 3	116 35	117 8	117 40	118 13	44
12	111 32	112 4	112 36	113 7	113 39	114 11	114 43	115 15	115 47	116 20	116 53	117 26	48
8	110 42	111 14	111 46	112 18	112 50	113 23	113 55	114 27	114 59	115 32	116 5	116 39	52
4	109 52	110 25	110 57	111 29	112 2	112 35	113 7	113 39	114 12	114 45	115 18	115 52	56
VII. 0	109 2	109 35	110 7	110 40	111 13	111 46	112 18	112 51	113 24	113 57	114 31	115 5	V. 0
VI. 56	108 13	108 46	109 19	109 52	110 24	110 58	111 30	112 3	112 36	113 10	113 44	114 18	4
52	107 24	107 57	108 30	109 3	109 36	110 10	110 42	111 15	111 49	112 23	112 57	113 31	8
48	106 35	107 8	107 41	108 14	108 47	109 21	109 54	110 27	111 1	111 35	112 9	112 44	12
44	105 46	106 19	106 52	107 26	107 59	108 32	109 5	109 39	110 13	110 48	111 23	111 57	16
40	104 57	103 30	106 3	106 37	107 10	107 44	108 17	108 51	109 26	110 1	110 35	111 10	20
36	104 7	104 41	105 15	105 49	106 22	106 55	107 29	108 4	108 38	109 13	109 48	110 23	24
32	103 18	103 52	104 26	105 1	105 34	106 7	106 41	107 16	107 51	108 26	109 1	109 36	28
28	102 29	103 3	103 37	104 12	104 45	105 19	105 53	106 28	107 3	107 39	108 14	108 49	32
24	101 41	102 15	102 49	103 23	103 57	104 31	105 5	105 40	106 15	106 51	107 27	108 3	36
20	100 52	101 26	102 0	102 34	103 8	103 43	104 17	104 52	105 28	106 4	106 40	107 16	40
16	100 3	100 37	101 11	101 46	102 20	102 55	103 30	104 5	104 41	105 17	105 53	106 29	44
12	99 14	99 48	100 22	100 57	101 32	102 7	102 42	103 17	103 53	104 29	105 5	105 42	48
8	98 25	98 59	99 34	100 9	100 44	101 19	101 54	102 29	103 5	103 42	104 18	104 55	52
4	97 36	98 11	98 46	99 21	99 56	100 31	101 6	101 41	102 18	102 55	103 31	104 8	56
VI. 0	96 47	97 32	97 57	98 32	99 7	99 42	100 17	100 53	101 30	102 7	102 44	103 21	VI. 0

In South Latitude { *When Apparent Time is A.M. read the Azimuth from South to East.*
{ ——— " ——— *P.M.* ——— " ——— *South to West.*

TABLE IV.

Correction of quadrantal deviation by spheres.

10" Thomson compass and binnacle, patt. 47 (iron brackets).

Position of spheres to correct known values of co-efficient *D*.

Position of Spheres.	Amount of D that will be corrected with different sized Spheres.					
	5" Spheres	6" Spheres	7" Spheres	8½" Spheres	10" Spheres	12" Spheres
	° ′	° ′	° ′	° ′	° ′	° ′
Close up*	3 32	4 2	5 25	7 2	8 40	11 22
Inches.						
Set out ·1	3 28	3 57	5 20	6 54	8 30	
·2	3 23	3 51	5 14	6 47	8 21	
·3	3 18	3 47	5 9	6 40	8 12	
·4	3 13	3 42	5 3	6 32	8 4	
·5	3 10	3 39	4 58	6 25	7 57	
·6	3 5	3 35	4 53	6 19	7 50	
·7	3 2	3 32	4 49	6 12	7 42	
·8	2 59	3 29	4 44	6 7	7 34	
·9	2 56	3 26	4 40	6 1	7 28	
1·0	2 54	3 23	4 36	5 55	7 20	
1·1	2 52	3 20	4 33	5 50	at extreme	
1·2	2 50	3 17	4 30	5 45		
1·5	2 44	3 9	4 20	5 35		
2·0	2 38	2 59	4 5	at extreme		
2·5	2 30	2 51	at extreme			
3·0	2 26	2 45				
3·5	2 21	at extreme				

* Distance of centre of Compass to the nearest point of Spheres in the position "close up" = 8·5 inches.

TABLE V.

THE VALUES OF CO-EFFICIENTS *B*, *C*, *D*, AND *E* FOR EACH POINT OF THE COMPASS.

Co-efficients.	POINTS OF THE COMPASS.							Co-efficients.
	1	2	3	4	5	6	7	
°	°	°	°	°	°	°	°	°
1	0·2	0·4	0·5	0·7	0·8	0·9	1·0	1
2	0·4	0·7	1·1	1·4	1·7	1·8	1·9	2
3	0·6	1·1	1·7	2·1	2·5	2·8	2·9	3
4	0·8	1·5	2·2	2·8	3·3	3·7	3·0	4
5	1·0	1·9	2·8	3·5	4·1	4·6	4·9	5
6	1·2	2·3	3·3	4·3	5·0	5·5	5·9	6
7	1·4	2·7	3·9	4·9	5·8	6·5	6·9	7
8	1·6	3·1	4·5	5·6	6·6	7·4	7·9	8
9	1·8	3·5	5·0	6·4	7·5	8·2	8·8	9
10	2·0	3·8	5·6	7·1	8·3	9·2	9·8	10
11	2·2	4·2	6·1	7·8	9·2	10·2	10·8	11
12	2·3	4·6	6·7	8·5	10·0	11·1	11·8	12
13	2·5	5·0	7·2	9·2	10·8	12·0	12·8	13
14	2·7	5·4	7·8	9·9	11·6	12·9	13·7	14
15	2·9	5·7	8·3	10·6	12·5	13·9	14·7	15
16	3·1	6·1	8·9	11·3	13·3	14·8	15·7	16
17	3·3	6·5	9·5	12·0	14·1	15·7	16·7	17
18	3·5	6·9	10·0	12·7	15·0	16·6	17·7	18
19	3·7	7·3	10·6	13·4	15·8	17·6	18·6	19
20	3·9	7·7	11·1	14·1	16·6	18·5	19·6	20
21	4·1	8·0	11·7	14·9	17·5	19·4	20·6	21
22	4·3	8·4	12·2	15·6	18·3	20·3	21·6	22
23	4·5	8·8	12·8	16·3	19·1	21·3	22·6	23
24	4·7	9·2	13·3	17·0	20·0	22·2	23·5	24
25	4·9	9·6	13·9	17·7	20·8	23·1	24·5	25
26	5·1	9·9	14·4	18·4	21·6	24·0	25·5	26
27	5·3	10·3	15·0	19·1	22·4	24·9	26·5	27
28	5·5	10·7	15·6	19·8	23·3	25·9	27·5	28
29	5·7	11·1	16·1	20·5	24·1	26·8	28·5	29
30	5·9	11·5	16·7	21·2	24·9	27·7	29·4	30

TABLE VI.

Semicircular Deviation.

Correction of Constant *c* by Flinders Bar.

Table of Equivalent lengths of Flinders Bar to correct values of *c*.

Value of *c*.	Amount of deviation to be corrected in South of England where tan. dip = 2·33.	Length of bar in inches.
	° ′	″
·01	1 20	6·5
·02	2 40	8·2
·03	4 00	9·5
·04	5 20	10·8
·05	6 40	12·2
·06	8 00	13·2
·07	9 25	14·2
·08	10 45	15·2
·09	12 06	16·3
·10	13 30	17·4
·11	14 50	18·4
·12	16 15	19·5
·13	17 35	20·6
·14	19 00	21·9
·15	20 30	23·1
·16	21 55	24·4

Note.—These values have been computed for the case of $\lambda = 1$ for an average Flinders bar of malleable iron, 3 inches in diameter, at a distance of 10·5″ centre of Compass to centre of bar, and made up of different lengths. If *c* be known, or can be assumed, the equivalent length of bar can be at once placed in position.

When *c* has the sign + on the after side of Binnacle.

When *c* has the sign − on the fore side of Binnacle.

These values of *c* and equivalent lengths of bar are chiefly intended for a first adjustment—the Flinders bar may require subsequent re-adjustment.

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CHARTS

CHART I.—LINES OF VARIATION FROM "ADMIRALTY MANUAL OF DEVIATION."

Chart I.

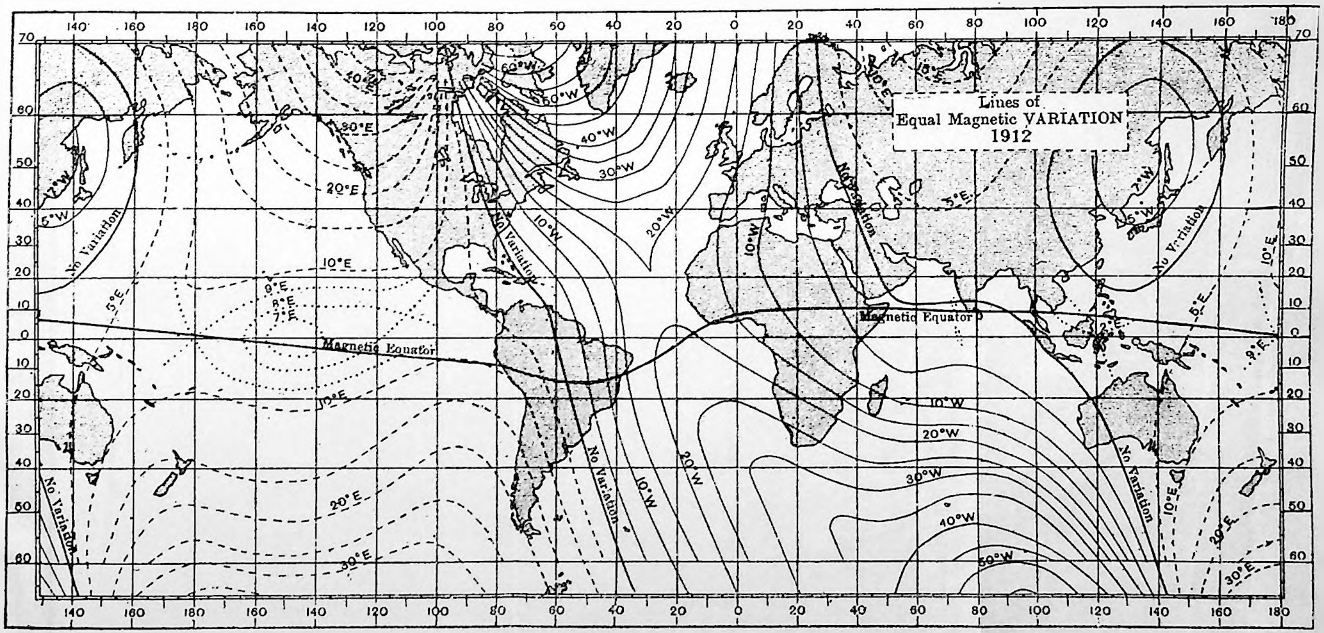

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CHART II.—LINES OF DIP, FROM "ADMIRALTY MANUAL OF DEVIATION."

Chart II.

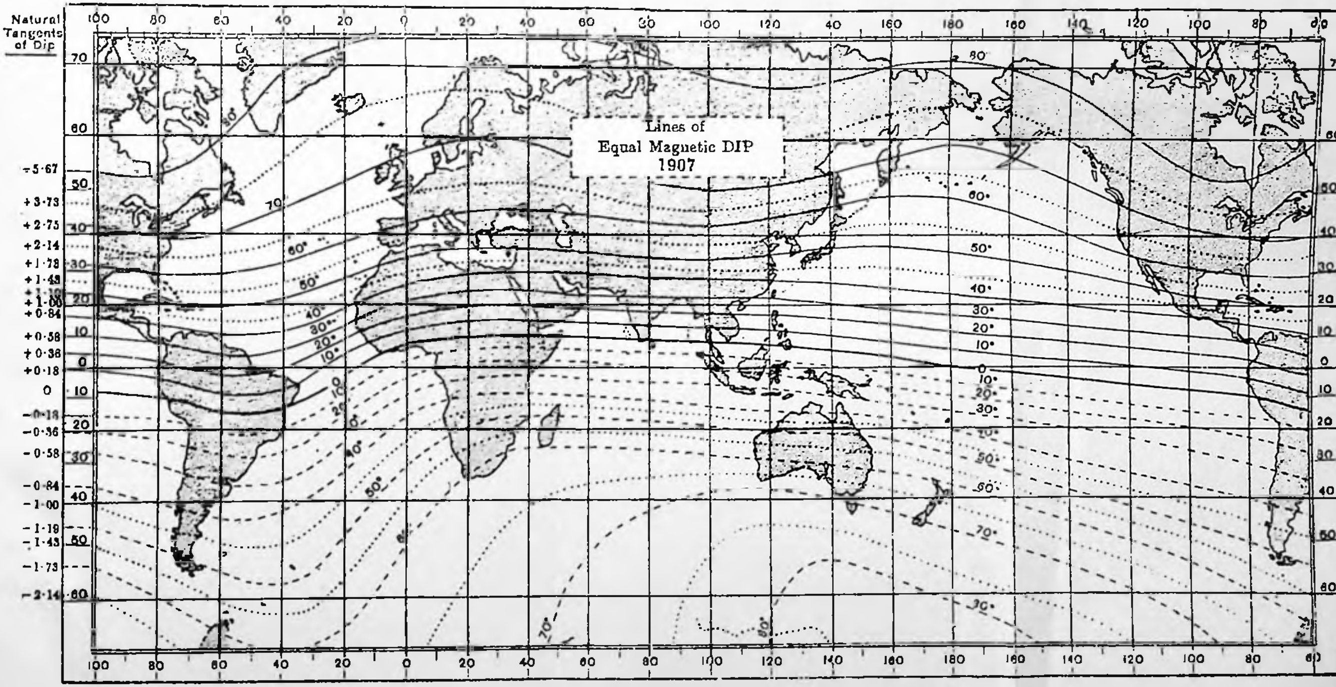

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CHART III.—LINES OF EQUAL HORIZONTAL FORCE, 1905, FROM "ADMIRALTY MANUAL OF DEVIATION."

[Horizontal Force at Greenwich = 1·0 = H]

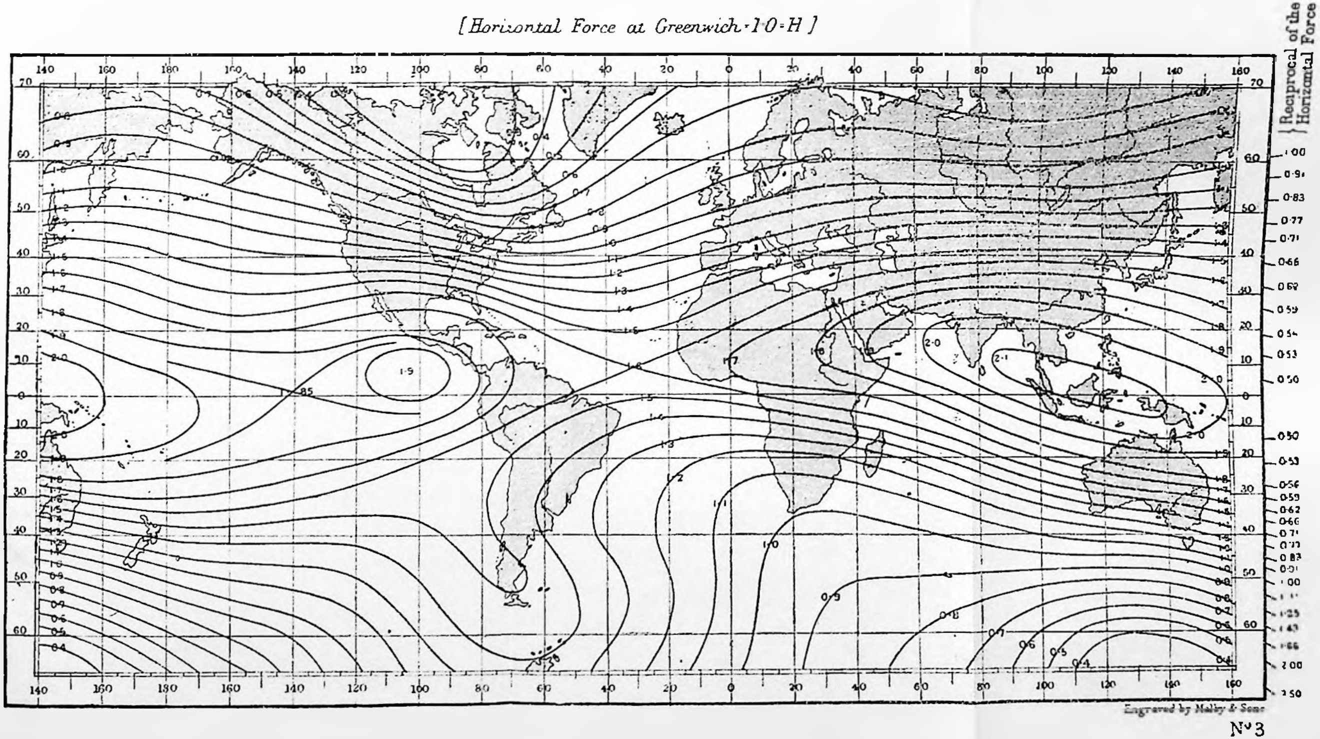

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CHART IV.—LINES OF HORIZONTAL FORCE, FROM "ADMIRALTY MANUAL OF DEVIATION."

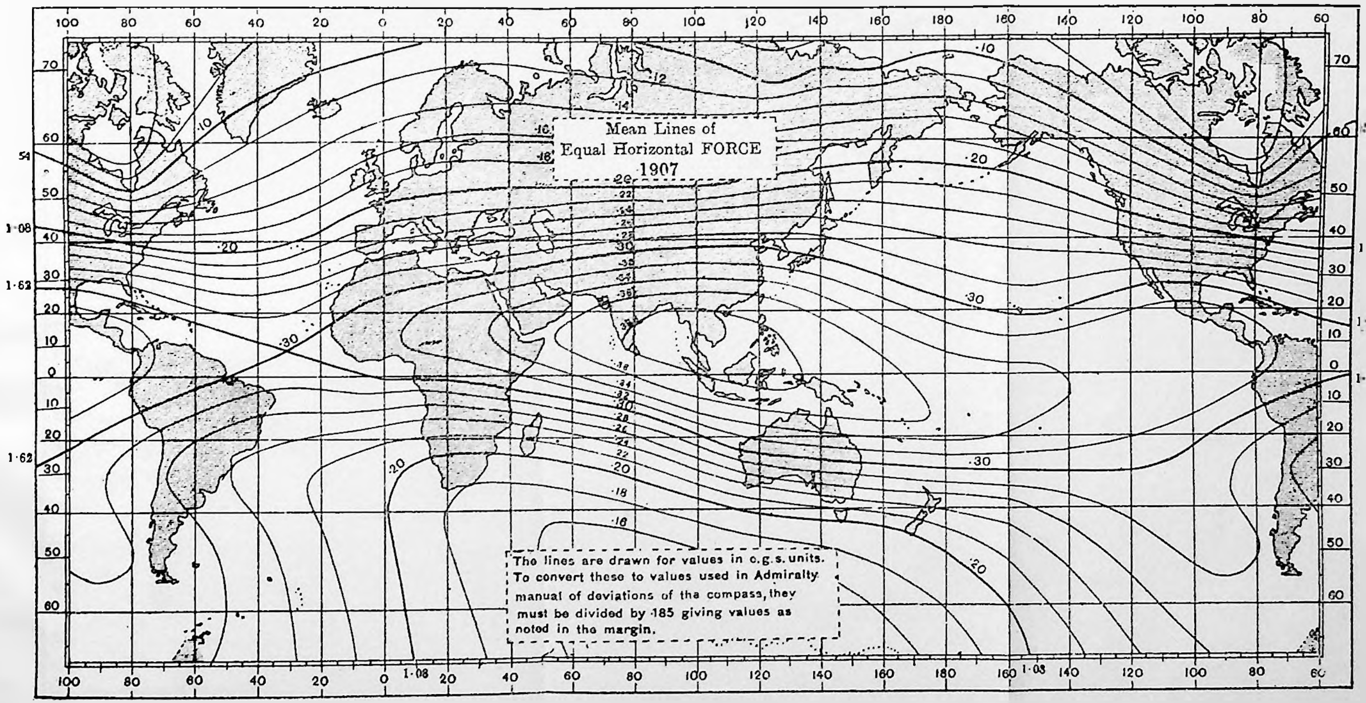

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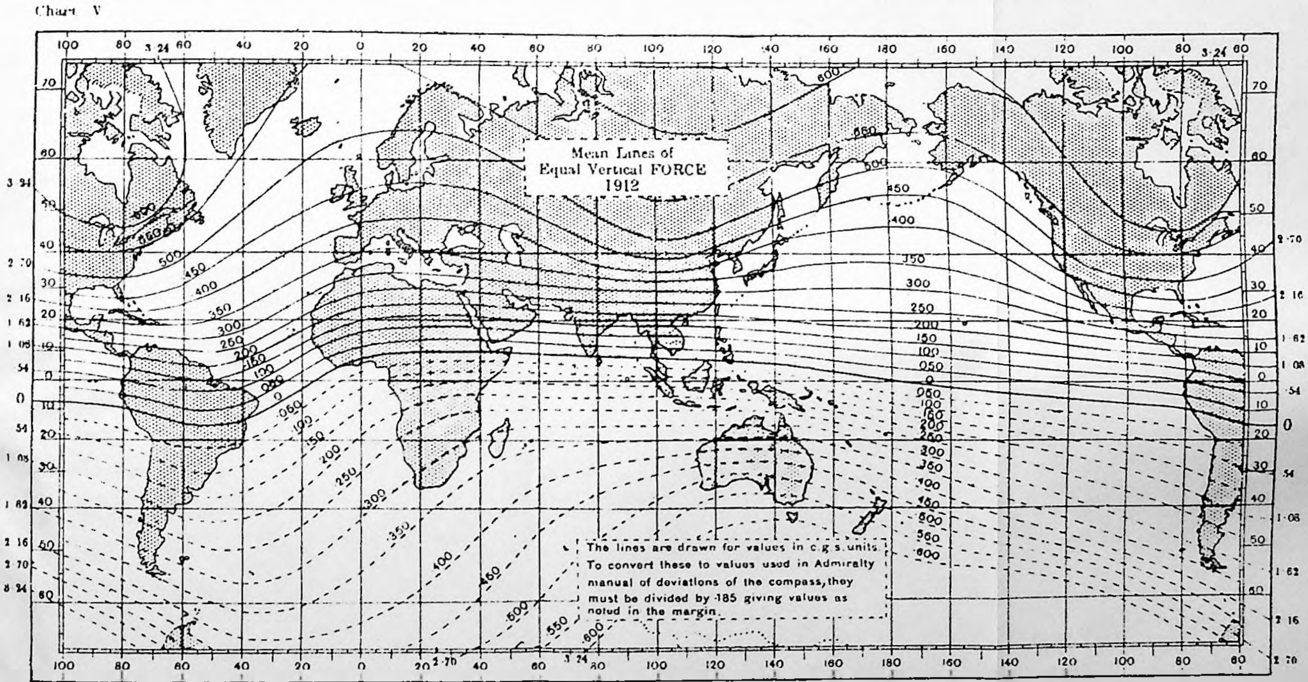
CHART V.—LINES OF EQUAL VERTICAL FORCE. FROM "ADMIRALTY MANUAL OF DEVIATION."



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